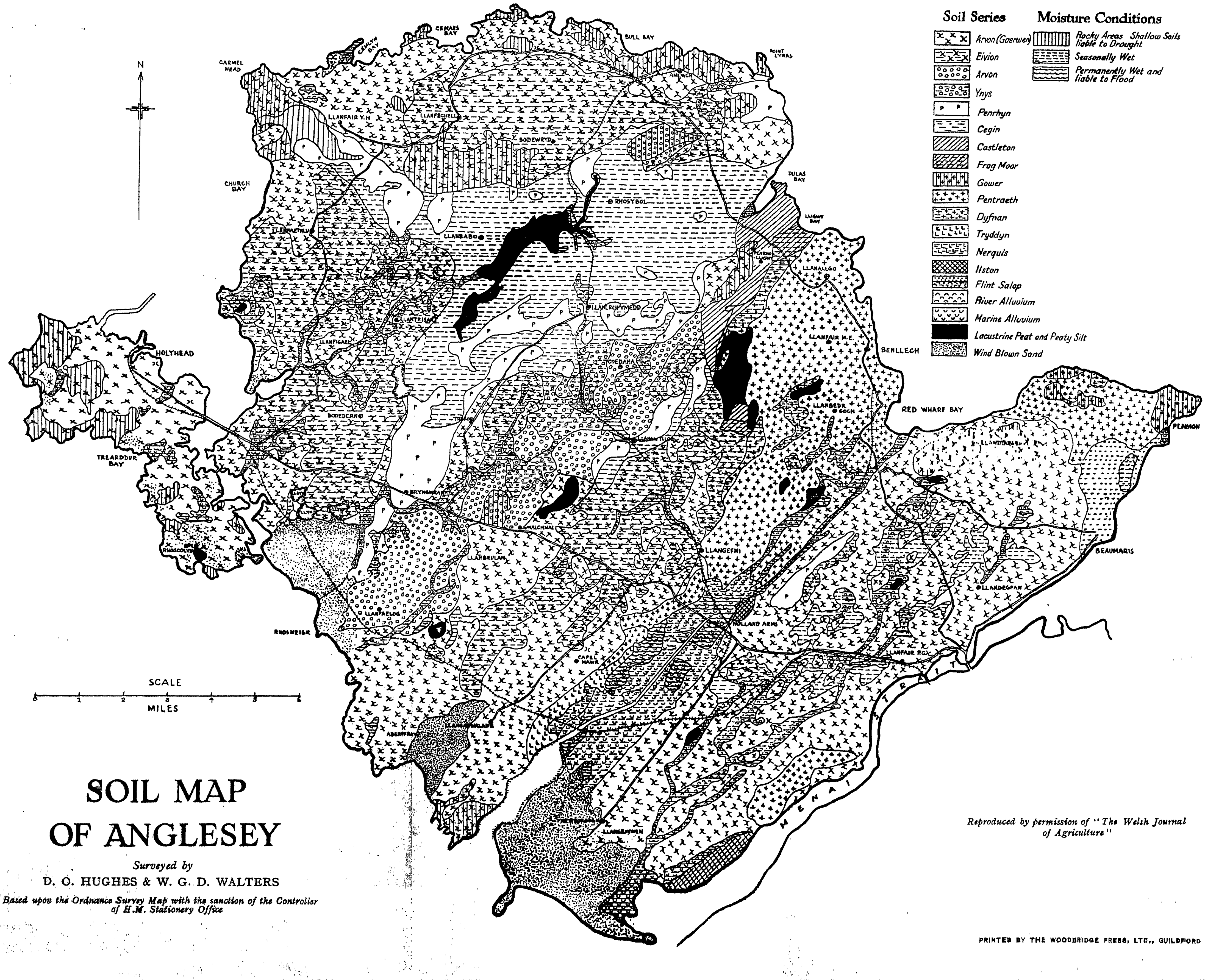
MOTHER EARTH

Praised be, my Lord, for our sister,
Mother Earth, which doth sustain
and keep us, and bringeth forth
divers fruits, and flowers of many
colours, and grass

ST. FRANCIS OF ASSISI

Canticle of the Sun



SOIL MAP OF ANGLESEY

Surveyed by

D. O. HUGHES & W. G. D. WALTERS

Based upon the Ordnance Survey Map with the sanction of the Controller of H.M. Stationery Office

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MOTHER EARTH

Being Letters on Soil

addressed to

Sir R. George Stapledon

C.B.E., M.A., F.R.S.

by

GILBERT WOODING
ROBINSON

M.A., SC.D.

Professor of Agricultural Chemistry
University College of N. Wales
Bangor

London

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PREFACE

Since this little book was first published, we have passed through the war, but the need for making the best possible use of our soil remains. Most of what was said in 1937 still stands, but a few necessary corrections and additions have been made.

G. W. ROBINSON.

University College,
Bangor.
July, 1946.

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LETTER I

INTRODUCTORY

MY DEAR STAPLEDON,

I have already written one book on soils*—a book in which I have tried to set forth our present state of knowledge of the soil as it appears to me. But I have been urged from more than one quarter to write a smaller book on soils with a rather different appeal. My counsellors have put forward a variety of suggestions, from which I have come to imagine the kind of book that might be written. It should be, I think, a book in which the more technical aspects of the subject are less severely treated than in " Soils "; a book in which the essential knowledge about soils is presented in clear perspective; a book that will give to workers in other fields, geologists, geographers, ecologists, agronomists, and Directors of Plant Breeding Stations, all they need to know for the benefit of their own studies. But I have ventured to cherish a further hope, namely, that I might write a book that would interest the general reader, perhaps even the farmer and the landowner, in the story of the soil, for I believe

* Soils, their Origin, Constitution, and Classification. An Introduction to Pedology. 2nd Edition reprinted, 1937, Thos. Murby & Co. (Allen & Unwin).

that this story is part of the *divini gloria ruris* so dear to both of us.

For the past two or three years, I have been turning over in my mind the idea of this little book on soils; but I have found great difficulty in imagining its broad outlines. Perhaps my chief difficulty has been the choice of a title, for I believe that a title may make or mar a book. And now it has occurred to me to cast my thoughts into the form of "Letters on Soil." I need not enter into the considerations that weighed with me in choosing this particular literary device. Perhaps the chief consideration was the possibility that it offered of speaking in a more intimate and direct way than in formal writing.

The success or failure of a series of letters must depend in no small measure on the kind of person to whom they are addressed. And here, my dear Stapledon, I count it a real and happy inspiration to have thought of you as a possible target for my epistolary shafts. You are vitally interested in the Land, and the Land is the Soil, even although you may be a little doubtful of the value of soil scientists, if not of soil science itself.

I know that you are deeply interested in the application of scientific theory to practice. You would hold, I think, that the value of the study of soils lies in its application to practice. But if I thought that your interest in the soil was simply utilitarian, I should feel that we had little common ground. I cannot help feeling that you have a deeper interest or you could not have written

"The Land, Now and To-morrow." You love the land, and that means the soil, for its own sake. And I am equally sure that all the great leaders in agricultural history have loved the land for its own sake, and have found in its cultivation the expression of their genius. Farming is a vocation, not a trade.

I hope in these letters both to interest you in the soil as a wonderful work of Nature—a part of a still greater pattern—and also to satisfy, so far as I am able, your thirst for useful information. What I do not propose is to write a concise manual of soil improvement. I shall try rather to give you a series of essays on the soil, viewed from the philosophical standpoint. It is the standpoint that appeals to me, for if I may, without profanity, borrow from the language of mysticism, I am attracted rather to the contemplative than to the active life, although I know that the good life requires a due balance of both.

I have often attempted to vindicate the philosophical approach to problems of the soil and I will affirm again that I believe this to be the only approach that gives any hope of real progress. Great inventions (many of which I deplore) have generally sprung from the application of principles discovered by pure scientists and not from *ad hoc* research. And, in the same way, I am sure that, as the principles of the soil and its life are discovered, applications (some possibly deplorable) to the practice of agriculture will follow naturally.

Unfortunately, the study of the soil was, until

recently, strictly tied to Agriculture as a branch of Agricultural Chemistry, and with disappointing results. Only during the present century has the soil been recognized as a natural body to be studied for its own sake by philosophical methods. This new approach is already justifying itself. Practical problems, such as reclamation of land from the sea in Holland, reclamation of alkaline irrigated lands in America and elsewhere, and problems of soil conservation in many lands, are being successfully tackled by the use of principles derived from the philosophical study of soils. In our own country, and particularly in Wales, there has been, until recent years, comparatively little interest in production, and the soil scientist has had little opportunity for service, apart from the giving of routine advice on questions of fertilization. But when increased production is required, the soil scientist will be ready to help, and the fundamental knowledge gained by the quiet research of the past half century will be of first importance in ensuring that development shall be along safe lines.

Remember that soil science is one of the youngest branches of natural philosophy and that it cannot be expected to provide a solution for all problems. Consider the probable state of geology if it had been strictly tied to mining and quarrying for the first century of its existence. And remember that the problems of crop production lie as much in the province of the plant physiologist as in that of the soil scientist. The master-problem of

crop production is that of the contract between soil and plant. If the nature of this contract is once understood, the solution of problems of crop growth follows naturally. This problem will not be solved by pot and plot experiments, but by the fundamental investigations of plant physiologists who are acquainted with the nature of the soil medium. This point is so important that I venture to illustrate it by the analogy of human medicine. Would you not admit that the only hope of real progress in preventive and curative physic lies in a better understanding of human physiology, rather than in the collection of data, even with the aid of statistical methods, on the reaction of individuals to drugs, diets, and régimes? Of course, an ultimate and complete solution of the problem of the growth of plants in soil is almost as unthinkable as a solution of the problem of life itself. But I do feel that the time is ripe for progress in our knowledge of the growth of plants. And in order to understand this mechanism we cannot know too much about the constitution of the soil medium.

I would wish everyone who is attempting to express himself by growing crops to become "soil-conscious." Believe me, my dear Stapledon, the soil has something to do with your problems and you cannot ignore it or dispense with studying it. You are primarily interested in growing crops and grass, and I cannot but believe that, if the fundamental principles of the soil are understood, you and your colleagues, rather

than the soil scientists, will find their applications to practice.

The letters I am about to write will form no systematic course of instruction. They will not form even an elementary text-book of soils.* They are to be considered rather as a series of essays, or even meditations, on topics relating to the soil. And because I am writing for other readers also, I have tried to simplify my narrative. In so doing, I hope I may not incur reproach from my learned colleagues for over-simplification. I am obliged to use a certain "economy" of truth; but I shall not wilfully mislead my readers. If I do mislead them I shall plead Dr. Johnson's famous excuse—pure ignorance. In the "Itinerary through Wales" of Giraldus Cambrensis, we read of one Melerius, who, after certain astonishing adventures on a Palm Sunday, acquired powers of divination by means of evil spirits: "*If he looked on a book, faultily or falsely written, or containing a false passage, although wholly illiterate he would point out the place with his finger. . . . If the evil spirits oppressed him too much, the Gospel of St. John was placed on his bosom, when, like birds, they immediately vanished; but when that book was removed, and the 'History of the Britons,' by Geoffrey Arthur, was substituted, they instantly appeared in greater*

* A reviewer of the first edition (*Nature*, October 30th, 1938) jumped to the conclusion that it was the author's lectures to first-year students in book form. Let me assure him that this is quite incorrect. *Mother Earth* is not even recommended as a text book to my students.

numbers, and remained a longer time than usual on his body and on his book." I hope that these letters will more nearly resemble the Gospel of St. John than Geoffrey of Monmouth's *History!*

However much I may simplify my account of the matters dealt with herein, I cannot avoid the use of some elementary scientific principles. I hope I am not unduly optimistic in assuming a grasp of these principles by the general reader. The simple arguments which I shall use will not be nearly so difficult to follow as the modern literature on matters of time and space. I am dealing neither with the infinitely great of the outer universe nor with the infinitely small of the atom, but with the homely middle region of the soil.

I am not sure that the general public is really interested in soil. I notice two types of reaction when I am introduced to people as a soil expert (a title I should never claim). Either the word "soil" suggests some ribald joke as to my occupation, or else my interlocutor asks me if I can tell him what is good for his garden! I have rarely met anyone interested in the soil for its own sake.

I believe that the story of the soil is as interesting as that of any other part of the great Universe, even although its transactions are fulfilled beneath our feet. May I conclude this opening letter by quoting from *Religio Medici?*

"*The World was made to be inhabited by Beasts, but studied and contemplated by Man;*

'tis the debt of our Reason which we owe unto God, and the homage we pay for not being Beasts; without this the World is still as though it had not been, or as it was before the sixth day, when as yet there was not a creature that could conceive, or say there was a World. The wisdom of God receives small honour from those vulgar heads that rudely stare about, and with a gross rusticity admire His works; those highly magnify Him, whose judicious enquiry into His Acts, and deliberate research into His Creatures, return the duty of a devout and learned admiration."

Ever yours,

G. W. R.

Letter II

SOIL OR *A* SOIL

My dear Stapledon,

I want, in this letter, to draw a distinction that at first may seem rather trivial, I mean the distinction between *soil* and *a soil*, between soil as a material and a soil as a natural body or individual. You yourself would readily admit that soil—soil material—is not the same as a soil in the field, which is the medium in which plants grow. And you would admit, even when we have found out everything that there is to be found about soil as material, that we have still to learn about its behaviour as a natural body or individual in the field. Much of the failure in applying science to soil problems has been due to this elementary mistake of confusing soil material with soil as an individual in the field, of confusing the laboratory specimen (for such it is when dried and prepared for analysis) with the natural body, the actual medium in which plants grow.

Now, we cannot dispense with the study of soil as a material. Indeed, it is most necessary for progress in the study of soils that we should understand as fully as possible the nature of the soil as a material. But we must first try to under-

stand the conception of soil as an individual. When I first began to work on soil survey in 1910, I was taught to sample both soil and subsoil. In the absence of any indications to the contrary, "soil" was taken as the top nine inches and "subsoil" as the second nine inches. Soil and subsoil together were supposed to form the soil individual as we recognized it then. The modern conception of the soil individual, which we owe largely to the Russian school, is merely a development of this idea. We now regard the soil individual as the *soil profile,* which consists of the complete succession of soil layers or *horizons* down to the geological parent material from which the soil is derived. I shall give you a description of an actual profile in a later letter.

And here we meet our first difficulty in defining what is meant by a soil profile, because it is often hard to decide where the soil profile ends and where the geological material begins: in other words, there is the problem of drawing the frontier between pedology (soil science) and geology. Actually, of course, pedology is a part of geology, but the problem of defining the scope of pedology *sensu stricto* still remains.

Let us dig (or, as we are getting on in years, cause to be dug) a deep trench or hole. Or let us save labour by examining the vertical section given by a quarry, gravel-pit, or new road cutting. Now obviously, at the surface, in the layers occupied by the roots of plants, we are in the soil profile. Equally obviously, at twenty or thirty

feet below the surface, in the live rock, raw gravel, clay, or sand, we are in the domain of the geologist. We might, of course, define the soil as the layers occupied by the roots of plants, and when we know how deep roots may penetrate, this may seem not an ungenerous definition. But let us look at the problem in another way.

If we examine the succession of strata far below the surface we see that the vertical differences in composition are due to geology; they were determined when the deposit—rock, drift, or alluvium —was laid down or formed, and have nothing to do with contemporary atmospheric processes or the influence of the soil flora and fauna. As we approach the surface, we reach a level above which the geological material shows alteration due to atmospheric and biological influences. We are now in the zone of superficial weathering and in our own country this is generally coterminous with the soil profile. This is not always the case, for under tropical and sub-tropical conditions the zone of superficial weathering may reach to fifty or sixty feet of depth, whilst the actual soil profile only occupies the upper portion of this.

I am afraid I have not made it very clear how the soil profile is defined; but actually there is no generally accepted definition. Yet, as one gains experience of soil profiles, one recognizes certain characteristic horizons as belonging to the soil profile, and these horizons are not found to be repeated within the geological profile. Under British conditions, the actual depth of the soil

profile varies from less than a foot in shallow upland soils to four feet or more in hillwash and deep glacial deposits.

By the soil profile, then, we understand a characteristic succession of horizons differentiated from the geological parent material under the influence of atmospheric conditions, of vegetation, and of the micro-flora and micro-fauna of the soil. If we know how to interpret the characters of these horizons, we can read the record of the development of the soil and draw inferences concerning its moisture and plant-nutrient conditions that will have an important bearing on problems of crop growth.

Soil profiles show differing degrees of development. Under natural vegetation, with flat or gently rolling topography, *mature* profiles are developed. In using the term mature I would not wish to convey any idea of permanent profile characters. Even under long-enduring constant conditions of climate, topography, and vegetation, profiles may undergo continuous change, possibly passing through a climax of one type of profile, succeeded by another line of development leading to another type of profile. It might be better to avoid the use of the term mature and to speak of *developed* profiles. With these we may contrast *immature* profiles, developed from recent deposits such as younger alluvia and dune sands, in which time has not sufficed for the differentiating of distinct soil horizons.

In a long-settled country like our own, mature

or developed profiles are the exception rather than the rule. Wherever land is cultivated, the original horizons down to the depth of cultivation become mingled in the cultivated layer and undergo modification owing to tillage, cropping, and manuring. The horizons below the cultivated layer are at first unaltered, but continued agricultural utilization involves a marked alteration from natural conditions, with the result that the profile, as a whole, gradually changes. It may, therefore, be permissible to speak of *agricultural profiles*. The profiles of permanent grassland soils also show considerable modifications from the profiles that formerly existed under virgin conditions.

Apart from the effect of cultivation in disturbing and altering the horizons of primitive soil profiles, it has also the effect of exposing the surface soil to erosion. Normal erosion, the transport of superficial material downhill until it reaches rivers, which carry it to the sea, goes on slowly even under virgin conditions. It is not a destructive process: indeed, by exposing fresh layers of parent material to weathering action it helps to maintain the supply of mineral plant nutrients within the soil profile. The actual magnitude of normal erosion may vary considerably, depending on the nature of the vegetative cover, the intensity of the rainfall, and the slope. When land is brought into cultivation it is exposed to much more rapid erosion by water or wind and the profiles may become truncated or, in extreme conditions, entirely destroyed.

We shall see at a later point how soil profiles are developed. For the present it is sufficient to notice that the soil profile is determined by the soil-forming factors and the geological parent material on which these factors operate. Among the soil-forming factors involved are natural vegetation, moisture conditions, temperature, and human or other interference. To these we may add time, as the factor determining the degree of maturity or development of the profile.

When soils have to be arranged in an ordered system of classification it is actually soil profiles that are classified. The soil profile is the natural individual in a system of soil classification just as the whole plant, not its leaves or root, is the individual in a botanical system of classification, and the whole animal, not its members, in a zoological system of classification. Without pushing the analogy too far we may liken the individual horizons of a soil profile to the parts or members of a plant or animal.

The soil profile is the significant factor in the study of the relationships of the soil to plants, not only because the profile embraces the root system of plants growing on the soil but also because the all-important factors, moisture and air, can be defined only in terms of the soil profile and not in terms of the laboratory samples. It is important also because a study of its characters can give information about its probable behaviour under different types of management and its suitability for different crops. In

the soil profile we ought to be able to read the past history of the soil and forecast its future possibilities.

I have spoken of the soil as a natural body and of the soil profile as the soil individual and the unit of study. But it must not be supposed that soils can be arranged into as orderly a classification as that of plants and animals. We can imagine an arrangement of soils into orders, genera, and species. But the conception of a soil species is by no means so definite as that of an animal or plant species. Not only can we have transitions from one soil species to another, but in some cases the species only represents an ideal point in a graduated series. Again, whilst environment cannot affect the identity of an individual plant or animal, external factors may profoundly affect the character of a soil profile and may even alter its position in a major system of classification.

For the purpose of soil classification, some investigators have proposed to take account only of soil profiles under undisturbed virgin conditions occurring under flat or gently sloping topography. Such an approach to the study of soils implies the neglect of Man as a factor in soil development. Surely our study must envisage soils as they are, and if the soil profile has been modified through human intervention, it is the business of the pedologist to understand how this intervention has operated.

Without withdrawing attention from the soil

profile, I shall try to give you in my next two letters some account of soil as a material and of its constituents, especially soil organic matter or humus, which shall have a letter all to itself. I shall then try to explain the meaning and significance of soil structure with special reference to the subject of tilth. Thereafter, so far as I speak about soil, I shall be mainly concerned with soils considered as profiles.

Ever yours,

G. W. R.

Letter III

SOIL MATERIAL

My dear Stapledon,

In my last letter I contrasted *soil* and *a soil* and emphasized the importance of the profile as the unit of study. But in order to understand *a soil* we must first know something about *soil*. In the present letter I propose to consider soil as a material.

Let us suppose we have a quantity of soil just as it comes from the field. We shall note in the first place the presence of stones, which are, of course, fragments of rock. If the stones are angular and all of one kind, we may reasonably infer that the soil has been derived by the weathering in place of the rock from which the soil has been formed. But if they are rounded they suggest travelled and possibly mixed material such as glacial drift or coarse alluvium. In alluvium, however, stones are more often absent. Material transported by wind is also stoneless.

For our laboratory examination we shall find it convenient to remove stones before proceeding further. The soil is first dried at about 40° C. and the stones removed by a sieve with 2mm. round apertures. The use of a 2mm. sieve is,

of course, quite arbitrary, and in some systems of analysis 3mm. or more is used as the limit. In order to separate the stones from the fine earth, it is necessary to break down all clods, so that what remains behind on the sieve consists simply of stones and gravel. The proportion of stones to the original soil can readily be obtained by weighing. In ordinary agricultural soils, the proportion of stones and gravel does not often exceed 10%. Soils derived from the Bunter Pebble Beds, Clay-with-Flints, and most of the hard ancient rocks are generally stony and may show up to 20 or 30% of gravel and stones. Very high proportions of stones are found in many of our upland soils. It is by no means uncommon to find 50% or more of the soil consisting of gravel and stones. Indeed, the subsoil horizons in some of our Welsh uplands consist mainly of rock brash with a matrix of finer soil.

Now stones in moderation, say up to about 10%, are probably an advantage. They offset to some extent the undesirable properties of clay, they facilitate drainage, they render the soil warmer, and they help to check losses by evaporation during drought. But we must remember that they do not yield available plant food and, therefore, in very stony soils, figures for available plant food obtained by analysis must be corrected for stones present. For example, taking two million pounds as the weight of an acre of top-soil, an available lime content of 0·2% would mean about 4,000 lbs. per acre. But if 50% of

stones were present, this figure would be reduced to 2,000 lbs.

Returning to our fine earth, which has passed the 2mm. sieve, we note that it contains fragments of all sizes from those of small gravel or coarse sand that have just got through the sieve down to particles indistinguishable by the naked eye. Actually, the finer particles are to a large extent stuck together into small crumbs or compound particles. These compound particles or crumbs are held together by the so-called *colloidal matter*, which consists of clay and humus (soil organic matter). In certain cases calcium carbonate may also have a cementing action. Now we can, by methods that I need not describe here, break down these aggregates or crumbs and obtain the ultimate particles of the soil free of each other. It is then possible to submit them to mechanical analysis and determine the percentage of :—

Fractions	Diameter limits mm.
Coarse sand	2–0·2
Fine sand	0·2–0·02
Silt	0·02–0·002
Clay	$<$0·002

A mechanical analysis gives in numerical form the kind of information given by the practical man when he describes his soil as a sand, sandy loam, light loam, heavy loam, or clay. Here are some figures for the percentage of the different fractions in typical soils :—

	Sandy Loam	Light Loam	Heavy Loam	Clay	Heavy Clay
Coarse Sand	66·6	27·1	13·6	0·9	1·0
Fine Sand	17·8	30·3	17·4	7·1	4·1
Silt ...	5·6	20·2	24·7	21·4	7·9
Clay ...	8·5	19·3	35·1	65·8	82·8

You will see that the fractions do not add up to 100. This is because (*a*) the soil used for analysis always contains a certain amount of moisture; (*b*) any calcium carbonate present is shown separately; and (*c*) organic matter (humus) dissolved during analysis is not reckoned in.

If the soil as a whole, including the fractions isolated in mechanical analysis, is examined closely, it is seen that the larger particles, down to about 2mm. diameter, are mainly fragments of rock, whilst the particles from 2mm. down to about 0·002mm. diameter are fragments of rock-forming minerals such as quartz, felspars, micas, hornblende, and the like. Below about 0·002mm. diameter there is a marked change in the character of the particles. Rock-forming minerals such as quartz and felspars disappear and their place is taken by minerals not ordinarily present in original rocks. This fraction, consisting of particles below 0·002mm. in diameter, therefore, differs profoundly from the coarser material. During recent years much work has been done on the constitution of the so-called *clay fraction*. As you may expect, it differs considerably in different soils, but certain common characters may be noted, and will now be briefly enumerated.

Apart from any difference in chemical character, the clay fraction is distinguished by its great development of *specific surface*. To explain what I mean by this, let us suppose that we have a cube, 1cm. by 1cm. by 1cm. The total area of the six faces is six square centimetres. If we could now take this cube and slice it up into cubes 1mm. by 1mm. by 1mm. we should get 1,000 such small cubes, and the total area of each would be $6 \times 0{\cdot}1 \times 0{\cdot}1 = 0{\cdot}06$ square centimetres. But as there are 1,000 of them, the total area would be 1,000 times $0{\cdot}06 = 60$ square centimetres. Thus, by subdividing our material we can increase its total surface. The same argument applies to material of any shape. The more finely it is subdivided, the greater will be the total surface per unit weight.

We have seen that the clay fraction is defined as consisting of particles less than 0·002mm. in diameter. This is only the upper limit; the lower limit is not easy to define, but there is some evidence for placing it at about 0·00006mm. Perhaps it would be more correct to say that the clay behaves as if it had such a lower limit. If we make such an assumption and calculate the specific surface, we get as the total area of one gram of an ordinary clay fraction about 200,000 square centimetres. It is the clay which is responsible for most of the surface development of soils. I have calculated the total surface per gram of a number of soils. The figures are given in the following table:—

Soil				Estimated surface in sq. cms. per gram
Sandy soil	...	...	...	12,000
Shaly, light loam		...	...	33,000
Clay subsoil	...	...	...	72,000
Raw clay ...	...	...	...	99,000
Clay fraction below 0·002mm.				195,000
Tropical clay	...	...	...	272,000

Now, apart from the fact that the clay fraction differs chemically from the coarser fragments of the soil material, this enormous development of surface in the finer fractions of the soil is of great significance. Take water retention, for instance. If a pebble is dipped into water, and then allowed to drain, a certain amount of water is held by surface tension; the pebble is said to be wet. Now if the pebble were crushed into smaller fragments the total area would be increased and much more water could be held by surface tension. It is evident, then, that the fine state of subdivision of the clay, or in other words, its enormous surface development, is largely responsible for its great capacity for retaining water. Apart from the retention of water by the soil when it is actually wet, water is also held by hygroscopic action, even in air-dry soils. This is essentially a surface action and is shown in a marked degree by the clay fraction. In addition to its great capacity for water retention, the clay fraction has the property of expanding on being wetted, and of shrinking on drying. Anyone familiar with a clay country will have noticed the

wide and deep cracks in grass fields during drought.

A further property of clay is *plasticity,* shown when soils are wet, and *cohesion,* whereby clods are formed on drying, of which more presently. It is noteworthy that a comparatively small amount of clay will enable a soil to set into hard clods on drying. I have noticed this particularly in some of the lighter boulder clay soils derived from Triassic material.

Surface development has an important effect on solubility and chemical reactivity. The more a material is subdivided the greater will be the proportion of atoms or atomic groups at the surface and, therefore, capable of reacting chemically. This can be illustrated in a homely fashion. There is a certain kind of sugar, I'm sure you know it, called candy, which consists of large sugar crystals sticking to thin string or thread. If you use this in coffee, you find that it dissolves so slowly that your coffee will probably be cold before it has dissolved. On the other hand, finely crystalline sugar dissolves almost instantaneously. The reason that finely powdered material dissolves more quickly is simply because it has a greater surface development. We should expect the clay fraction, therefore, to be chemically the most active part of the soil, and this is actually the case.

But this greater chemical reactivity of the clay fraction is not due entirely to its enormous surface development. The clay fraction includes

minerals that have been formed from the decomposition of minerals present in unweathered rocks. These minerals, *e.g.* kaolinite, beidellite, and montmorillonite, to name the more important of those that have been recognized, are actually more reactive than the original minerals from which they have been derived. In addition to definitely recognized minerals such as those mentioned, there may also be present in the clay fraction material that is chemically reactive, but apparently possessing a less definite chemical constitution, and not even finely crystalline. The clay fraction of certain soils may also contain free hydrated ferric oxides, which confer on it a reddish or yellowish colour. Hydrated alumina may also be present.

Much remains to be discovered about the nature of the constituents present in the clay fraction. One of the tasks awaiting soil chemists is the survey of the clay fraction of different types of soil. It is certain that there are important differences between soils in this respect, both in the actual constituents present and also in their relative proportions. We may distinguish, however, two extreme types, the one with high silica and low sesquioxides (alumina and ferric oxide), and the other with high sesquioxides and low silica. Between these extremes all gradations can be found. Siliceous clays are more sticky, plastic, and cohesive than sesquioxidic clays, which tend to be friable and non-plastic.

We must now discuss the organic matter of soil. If we look at a heap of soil we can generally

pick out recognizable fragments of leaves, roots, etc., and, by close search, seeds. But even if we could pick out all the material recognizable as plant remains we should not find that it amounts to more than about one-tenth of the total organic matter present. The bulk of the organic matter of the soil occurs as dark-coloured amorphous material, which we may conveniently term *humus*. Humus is the characteristic organic ingredient of soils. It has resulted from the profound alteration of plant residues by the agency of fungi, bacteria, and other micro-organisms in the soil. I shall deal with the subject of humus in another letter.

Humus occurs in soil in close association or perhaps in loose chemical combination with clay. This clay-humus association is called the *colloidal complex,* and is the seat of most of the chemical and biological activity of the soil. The properties of soil are determined mainly by the amount and nature of the colloidal complex. Note that the nature of the colloidal complex is of the highest importance. We may have a set of soils containing the same proportion of colloidal matter but differing totally in properties, for in one the complex may be mainly humus, giving us a peat soil, in another the complex may be mainly siliceous clay, giving us a tenacious heavy soil, whilst in a third the complex may be sesquioxidic clay, giving us a friable soil, such as the lateritic soils of the tropics.

I have said that the colloidal complex is the

reactive fraction of the soil. Both clay and humus are potentially of an acid character, and the clay-humus complex actually behaves in many respects as a weak, insoluble acid, partially or completely combined up with bases, of which the principal base is lime. When bases are present in very small proportions, as in most of our Welsh upland soils, the soil is said to be *base-unsaturated,* and the acid properties of the clay complex are dominant. On the other hand, in soils containing abundance of calcium carbonate, such as chalk soils, the acid properties are recessive, for the complex is completely saturated with calcium : we have, so to speak, a *calcium soil.*

When the colloidal complex has a very low base-status, *i.e.*, when it is present in its acid form, the mineral portion—the clay complex—becomes relatively unstable, and may undergo a chemical decomposition that varies in intensity and character with the extent to which the base-status has been lowered, and also with the presence or absence of a raw humus layer in the upper horizons of the soil.

Summarizing what I have tried to expound so far, we may say that soil as examined in the laboratory consists of a framework or skeleton of relatively non-reactive material, formed mainly of unweathered or unweatherable mineral fragments, and a reactive portion, the so-called colloidal complex, which is partly mineral (the clay fraction or clay complex) and partly organic (the humus complex). The colloidal complex acts

as a weak insoluble acid that can react with bases; in nature, principally with lime.* The extent to which the acid colloidal complex is combined up with bases has a profound effect on the general character of the soil. On the one hand, we have acid soils, in which the acidity of the colloidal complex is at maximum owing to lack of bases; on the other hand, we have soils in which the soil acids are neutralized by combination with bases, and excess bases are present as carbonates, giving the soil an alkaline reaction. But more of this when we consider the very practical problem of liming and soil acidity.

We must now notice that the soil, as we examine it in a dried laboratory sample, differs in important respects from soil in the field. In the latter case we must also include in our view the *soil solution* and the *soil air*. The soil solution, the moisture actually present in the soil, is the dilute aqueous solution from which, by absorption through their roots, plants obtain their nutrient requirements. It would naturally be interesting to know something of the composition of the soil solution in different soils, and how it varies from time to time in the same soil. Actually it is difficult, if not impossible, to isolate it unchanged. The smaller the amount of moisture present in the soil, the more tenaciously

* The amount of lime associated with the clay and humus, the so-called *exchangeable lime,* is generally an indication of the base-status, since lime usually accounts for about 80% of the total bases present. The other bases are magnesia, potash, and soda. The last two are normally present in smaller amounts than is magnesia.

is it held, so that although it is possible by high pressure or centrifuging to obtain soil solution from relatively wet soils, it is exceedingly difficult to obtain it from soils at ordinary moisture contents. Displacement of soil solution by other liquids has been tried but has only a limited application.

The composition of drainage waters may give us some indication of the relative proportions of different constituents in soil solutions, allowing that the former are considerably more dilute. It is not, however, possible to obtain the composition of soil solution simply by multiplying drainage water figures by a factor, because the solubility relationships are exceedingly complicated, mainly on account of the presence in the soil of active colloidal material.

We may suppose that, as soils become dry, the soil solution becomes more concentrated, and this may be a contributory cause of the wilting (loss of turgor) that occurs when the moisture content of a soil falls below a certain point. As so little is known of the composition of the soil solution, and as it must vary from soil to soil, and within the same soil at varying moisture contents, I shall not attempt to instruct you any further on it, but merely report a deficiency of knowledge.

In a natural soil we must take into account the soil air. This differs from atmospheric air in two important respects. In the first place, it is usually saturated with water vapour, and in the second place it contains a much higher propor-

tion of carbon dioxide than the atmosphere. Over 1% of carbon dioxide is not unusual as a figure for the soil atmosphere, compared with about 0·03% in the air. The carbon dioxide originates from the respiration of plant roots and from the decomposition of organic matter in the soil. It varies from soil to soil, and from time to time in the same soil according to the intensity of carbon dioxide production. Carbon dioxide formed in the soil dissolves in the soil moisture, and there is thus a shifting equilibrium between dissolved carbon dioxide and free carbon dioxide in the soil. The dissolved carbon dioxide reinforces the solvent action of the soil moisture on the mineral matter of the soil, and thus plays an important part in weathering, and in the rendering available of plant nutrients.

One final point remains to be noticed, namely, the *structure* of the soil. If we take a certain volume of dry soil, a proportion of this volume is occupied by what is called *pore-space,* the interstitial spaces between the particles. In ordinary soils the interstitial, or pore-space, is of the order of 50%. But it is not a fixed constant for a given soil, since it depends on the way in which the particles are packed together. If a soil consisted (as it never does) entirely of spherical particles packed together in closest arrangement, the pore-space would be 26%. The diagram in *Fig.* 1 illustrates this possibility. Where particles of different size are present, there is the possibility of smaller particles filling in the interstices

between larger particles, and the pore-space can be still further reduced. In *Fig.* 2 this possibility is shown diagrammatically. But owing to the

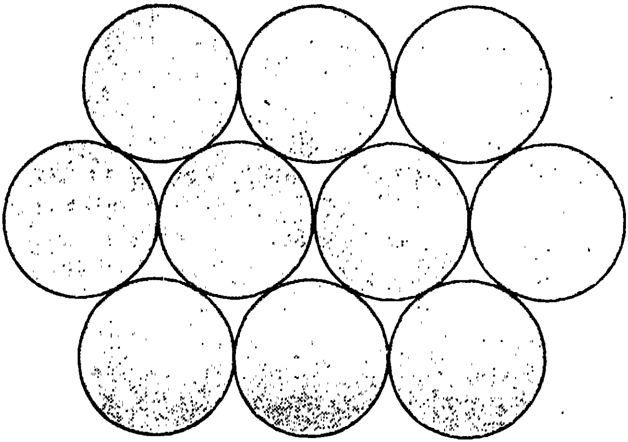


FIG. 1. Particles in close packing.

presence in actual soils of the clay-humus complex, the soil particles are grouped into compound aggregates or crumbs, so that there are two kinds of interstitial space, namely, the larger spaces between the crumbs and the finer spaces within the crumbs. The proportion of pore-space thus becomes greater than if the particles behaved independently of each other. I have shown this diagrammatically in *Fig.* 3.

The more a soil is aggregated into the crumb structure the greater is the pore-space. On the other hand, destruction of the crumb structure,

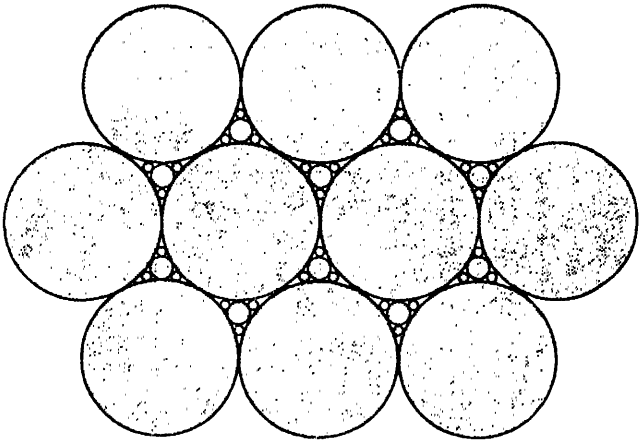


FIG. 2. Showing reduction of pore-space by packing of smaller particles in spaces between larger particles.

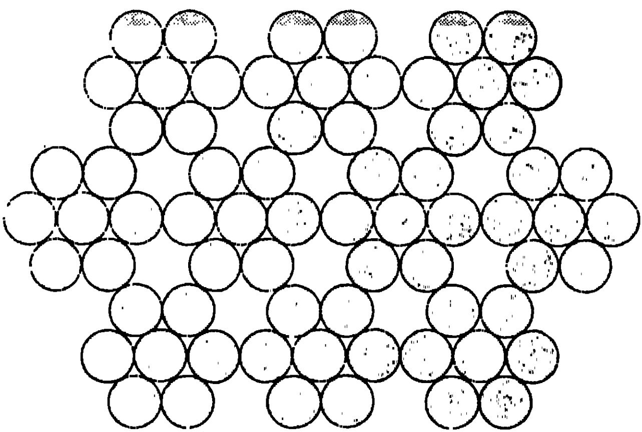


FIG. 3. Increase of pore-space by grouping of particles

e.g., by trampling or puddling, leads to a decrease in pore-space. In view of the importance of aeration for the health of the soil and the crops which grow on it, I need hardly tell you that the crumb structure is a GOOD THING,* and the other structure, the single-grain structure, a BAD THING. Crumb structure is, to use a picturesque expression of A. G. Street, the *fibre* of the soil. When I speak simply of structure, I mean this crumb structure, or fibre. When I speak of loss of structure, I mean loss of crumb structure, for the single-grain structure is no structure at all.

Ever yours,

G. W. R.

* Following the convenient nomenclature of Sellars and Yeatman in "1066 and All That."

LETTER IV

HUMUS

MY DEAR STAPLEDON,

I often reflect on the difference between a farm soil and a garden soil, but if I were asked to state in a few words in what the difference actually consists, I should find it rather difficult. If you visit an average farm and compare the soil of the garden with that of the fields, you will notice great differences. The garden soil is deeper, generally darker in colour, mellower in its tilth, and, if it is a well-kept garden, more productive. Now the garden was originally made from the same kind of soil as the adjoining fields, and the differences observed are due to the treatment that it has received. Briefly, this treatment may be summed up as continuous tillage, and the addition of large quantities of stable or farmyard manure: lime also has probably been given from time to time. I should be disposed to attribute most of the characteristics of the garden soil to the dressings of stable or farmyard manure that it has received. On analysis, the garden soil will be found to have, perhaps, 10 to 15% of organic

matter, whilst the adjoining field soil may have only about 5%.

An average dressing of farmyard manure will add 4 or 5 tons of organic matter per acre, which amounts to about 0·4 or 0·5% of the soil down to spade depth. If farmyard manure has been given regularly to a garden soil for generations, you may ask why the amount has reached only 10 or 15%. Well, the reason is that organic matter is continually undergoing decomposition, the same type of decomposition that it would undergo if burnt, namely, an oxidation to carbon dioxide and water vapour. The actual amount of organic matter or humus in a soil represents the balance between additions of organic matter and losses by decomposition. The liberal additions of farmyard manure maintain the garden soil at a higher organic matter level in spite of the fact that the continuous tillage to which it is subjected favours losses by oxidation.

We should now enquire into the general nature of the soil organic matter. If we take a spadeful of soil, we shall at once notice recognizable plant remains, fragments of roots, stems, and perhaps also leaves. We shall also, by minute search, discover seeds — weed seeds probably. But if we collected together all these plant remains, we should still find that the bulk of the organic matter present remained unaccounted for. About nine-tenths of the soil organic matter consists of a dark structureless material, which we call *humus*. This is the

characteristic organic matter of the soil. Unfortunately, and this seems rather a reflection on soil chemists, there is no method by which it can be isolated unchanged from the soil. It occurs associated in intimate mixture or even in loose chemical combination with the clay, forming the clay-humus complex, or colloidal complex of the soil. I need hardly say that the use of the term complex in this case, as in most other cases, betokens a certain amount of ignorance.

What is the origin of the soil humus? It is formed from the alteration or decomposition of organic matter added to the soil. Under natural conditions this means the decomposition of the remains of plants that have grown in the soil. In cultivated soils, we have as additional sources of humus, organic manures, of which the principal is farmyard manure; and farmyard manure consists mainly of the decomposed excreta of animals, mixed with the litter, usually straw, used in their bedding.

I will return later to the subject of farmyard manure, but now I must say something of the way in which plant remains undergo decomposition in the soil. These remains consist of dead roots within the soil, and withered stems and leaves on the soil. In forests, the most important contribution is from leaf-fall. Plant remains, for the most part, consist of the fibrous constituents of plants, and are poor in nitrogenous compounds (proteins), starches, and sugars. In passing, we may note that owing to their poverty in nitrogen,

the ratio of carbon to nitrogen, the so-called C/N ratio, is very high, something of the order of 40 or more. Contrast this with the C/N ratio of humus, which is about 10.

The decomposition of plant residues added to the soil is almost entirely the work of the micro-population of the soil. In the first place there is the work of earthworms. Their main function appears to be the comminution and distribution of plant remains throughout the top layers of the soil. You have probably noticed the rapidity with which grass clippings left on a lawn disappear, owing to the action of earthworms. In some very acid soils, under coniferous forest or heath, earthworms are almost, if not completely, absent, and plant remains (leaf litter) then accumulate at the surface where, it is true, they undergo decomposition, but are only slightly incorporated with the underlying soil. In the tropics, the white ants (termites) fulfil a similar function to earthworms.

It does not appear that earthworms have much to do with the actual chemical decomposition of plant residues. This is almost entirely the work of fungi and bacteria. In very acid soils, such as those under coniferous forest or heath, fungi play the major part, but in less acid soils bacteria are the chief agents. The numbers of bacteria per gram of soil are, as you know, reckoned in millions. But it appears from recent work that their distribution is very uneven, as they tend to occur in "nests," being particularly abundant in the vicinity of dead or dying roots,

or indeed near any organic material ripe for attack by them.

Considering the decomposition of plant residues as a whole we may distinguish two main types, namely, (*a*) oxidation and (*b*) humification.

(*a*) Oxidation has the same result as combustion in oxygen. The organic matter becomes oxidized to carbon dioxide and water, and is, therefore, completely lost from the soil. The carbon dioxide, which may form up to 1% or more of the soil air, comes mainly from the biological oxidation of organic matter. Indeed, the carbon dioxide thus formed is the most important source of the atmospheric carbon dioxide that is utilized by plants in carbon assimilation. Oxidation is essentially destructive, and where this type of decomposition predominates, added organic matter rapidly disappears from the soil. It is favoured by moisture, warmth, and, above all, by aeration. It is remarkable how quickly organic matter can disappear from soils when conditions favourable for oxidation obtain, as, for example, in cultivated soils in the tropics. Even in our own climate, cultivation, by producing aèration, favours loss of organic matter. It may be added that the bulk of the humus is much less rapidly decomposed than recent plant remains. This is fortunate, because if it were as readily oxidized as these residues, organic matter would speedily be lost, with a host of undesirable consequences for plant growth.

(*b*) Whilst oxidation is destructive of organic

matter, the processes of the other type, namely, humification, are conservative in their effect. By these processes, plant residues become changed into the dark-coloured amorphous material, humus, which forms the greater part of the organic matter of soils. There are a number of different kinds of humification, not always as clearly distinguished as they should be.

The commonest kind of humification, in our country at least, is the so-called *anaerobic* humification, *i.e.*, the humification that takes place with absence or restricted supply of oxygen. Such conditions obtain where plant residues decompose under water, as in pond or lake mud. They also obtain in soils that are waterlogged. But even in well-drained soils there are periods when high moisture content results in anaerobic conditions. Apart from this, local anaerobic conditions may obtain within the soil crumbs of a well-aërated soil.

Whilst, in anaerobic humification, a certain loss of organic matter occurs as gaseous products, carbon dioxide, methane, etc., a considerable proportion, perhaps the bulk of the plant residues decomposed, is changed into humus. It appears that the fibrous constituent, lignin, plays an important part, and that humus consists largely of altered lignin combined with protein material, possibly of microbial origin. It will be easily seen that in wet soils the tendency will be for the residues of vegetation to accumulate as humus. In extreme cases, this accumulation may proceed

to the extent of peat formation. In certain types of peat, the material consists entirely of decomposed and decomposing plant residues, all connexion with the mineral subsoil being lost.*

In the second type of humification to be considered, the dominant factor is acidity or low base-status. The residues of vegetation growing in soils that are very poor in lime give rise to a raw humus layer, even although aeration may be good. Heath peat, formed under *Erica* (heather), *Calluna* (ling), or *Vaccinium* (bilberry) vegetation, and coniferous forest peat are examples of the type of material formed where acid humification is dominant. It may be seen also in the peaty mat formed in some poorer types of grassland, for example, the *Nardus* grassland of our uplands, although in such cases anaerobic humification may also play some part.†

There are probably other types of humification. The dark-coloured humus of the "black earths" of Russia and the "prairie soils" of North America does not appear to be satisfactorily explained by anaerobic humification, whilst acidity is excluded by their naturally high base-status. The soils of the humid tropics present a different problem. Here the humus is apparently much less dark in colour, so that one can easily under-estimate the

* It is possible that anaerobic humification may be chemical as well as microbiological. The formation of sphagnum peat is associated with low microbiological activity and may be to some extent chemical.

† The intense blackness of the peaty layer in many heath soils may be partly due to carbonaceous material which has been formed by heath fires.

amount of organic matter present in such soils. I have frequently been surprised at the high proportions present in tropical soils, where I should have expected the conditions to favour the rapid oxidation of organic matter.

The amount of organic matter in a soil, then, depends on (1) the rate at which organic matter is added to the soil either in the form of plant residues or as organic manures, and (2) the relative intensity of oxidative decomposition and humification. We shall, therefore, expect to find low organic matter where plant growth is scanty, as in deserts and in sand dunes, or where oxidative decomposition is favoured by warmth and aeration. On the other hand, bad aeration, due to water-logging, or acidity may encourage the conservative process of humification, and under such conditions organic matter as humus tends to accumulate.

Are we to consider humification as a Good Thing and oxidative decomposition as a Bad Thing, or *vice versa*. Well, both are Good Things when they do not operate excessively: both are Bad Things when they do operate excessively. If humification gets out of hand there is an accumulation of a sour type of humus and a general slowing down of biological activity in the soil, resulting in depressed fertility. On the other hand, if oxidative decomposition is too vigorous, the amount of organic matter in the soil becomes low, with loss of water-holding capacity, deterioration of fibre (structure), and general lowering of fertility.

Inasmuch as humification helps to build up and maintain the humus, which, in moderate proportion, maintains structure, water-holding capacity, and general fertility, it is a Good Thing. Similarly, inasmuch as oxidative decomposition is the source of the all-important carbon dioxide, and checks the accumulation of redundant humus, it also is a Good Thing. Fortunately, under sound systems of land utilization, there is little fear of either process getting out of hand.

Humus can exert its maximum effect on the physical condition of the soil only when it is formed in the presence of a sufficiency of lime. Humus in this condition is sometimes called *mild humus* in contrast with the so-called *raw humus* of acid peats. Mild humus is wholly favourable in its effect on the physical condition and tillage properties of soils, and is also associated with high microbiological activity. One of the chief aims in the reclamation of peaty soils, therefore, should be the transformation, by liming, of raw acid humus into mild humus.

It is rather interesting to compare the organic matter status of forest soils with grassland, prairie, and steppe soils, particularly if we take a line across a great continent like North America, where the transition from forest to grassland vegetation can be followed. As you know, the Eastern United States, with its humid climate, is a forest region. Going westward, the humidity falls off, and forest is succeeded by tall grass (prairie), which gives place to short grass, and

eventually to desert scrub. Now one might expect that there would be a progressive fall in organic matter status. Actually, in passing from forest to prairie there is a sharp rise in organic matter, for under comparable conditions, grassland soils contain considerably more organic matter than forest soils. This is due largely to the greater root development in the surface horizons of grassland soils, and the more intimate admixture of plant residues with the soil under grass than under forest, where the leaf-fall lies loosely on the surface, and is exposed to heavy wastage by biological, and, it may be, chemical oxidation. I should add that in passing away from the forest-prairie boundary to drier regions, there is a gradual fall in organic matter status in harmony with the decreasing amount of plant growth.

The agricultural utilization of soils imposes an artificial régime. It is generally supposed that the exploitation of virgin soil is accompanied by loss of organic matter, and this is generally true for steppe and prairie soils. The conversion of forest soils to intensive agricultural use, however, may result in an actual raising of the organic matter status. This is certainly the case where, as in Wales, the change is to grassland or to a system of agriculture with long grass leys in the rotation. On the other hand, where forest soils are brought into continuous arable cultivation, loss of organic matter occurs, often with disastrous results.

Intimately bound up with the general organic matter question is the "*nitrogen cycle*" in soils. At the outset we may enquire as to the source of soil nitrogen. To say that it originates from the nitrogenous constituents of plants that have grown on the soil is only to shift the enquiry a stage further back. Plants obtain their nitrogen from the soil in the form of nitrates or ammonium salts, but we have still to account for the presence of these "available" compounds of nitrogen.

A certain amount of ammoniacal and nitrate nitrogen is contributed in rainfall. This is about 4 lbs. of nitrogen per acre per annum under British conditions; a small amount, but possibly of significance considered over long periods. In the tropics, where thunderstorms lead to the formation of larger amounts of oxides of nitrogen in the air, the annual contribution of ammoniacal and nitrate (principally nitrate) nitrogen in rainfall may amount to as much as 50 lbs. per acre, which is an appreciable accession to the annual nitrogen requirements of crops or natural vegetation.

Whilst, even under British conditions, the cumulative effect of ammoniacal and nitrate nitrogen in rainfall on the nitrogen reserves of the soil cannot be ignored, it is probable that the fixation of nitrogen by bacteria is of greater importance. The fixation of nitrogen by bacteria associated with leguminous plants is a familiar story,* but fixation by free-living nitrogen fixing

* By leguminous plants we mean, of course, the bean, pea, and clover tribe. Long before their association with nitro-

bacteria is probably of equal importance, and we must also take into account possible fixation of nitrogen by certain algæ. Little is known of the way in which bacteria synthesize the chemically inert nitrogen of the atmosphere into organic combination. Of the importance of this fixation there is no doubt. Not only does the great family of leguminous plants obtain its nitrogen by this means, but the nitrogenous compounds built up by the free-living nitrogen-fixing bacteria readily undergo decomposition into the simpler forms of nitrogen requisite for the growth of non-leguminous plants.

It is a remarkable fact that although an acre of soil may contain several thousand pounds of nitrogen in organic combination, a dressing of nitrate of soda or sulphate of ammonia, giving 15 or 20 lbs. of nitrogen, often produces a big increase in the yield. It is obvious that by far the greater proportion of the soil nitrogen is not immediately available for the use of plants. Since plants require their nitrogen in the form of nitrates or ammonium salts, the processes whereby

gen-fixing bacteria was discovered, their favourable effect on succeeding crops was known. It is to this that Virgil alludes in the oft-quoted passage from the First Georgic:—

> "... *ibi flava seres, mutato sidere, farra,*
> *unde prius lætum siliqua quassante legumen,*
> *aut tenues fetus viciæ tristisque lupini*
> *sustuleris fragiles calamos silvamque sonantem.*"

"*Under another star, thou shalt sow yellow corn where thou didst take pulse, luxuriant with trembling pod, or the crop of slender vetch, or the fragile stems and rustling growth of bitter lupine.*"

complex organic nitrogenous compounds are broken down are of great importance for plant nutrition. This breakdown, of which the final stages are:—ammonium salts→nitrites→nitrates, is the work of a variety of fungi and bacteria, although the last two stages are the work of specific bacterial species.

Except in acid soils, the change from ammonium salts to nitrates *via* nitrites is more rapid than the production of ammonium salts. Therefore, ammoniacal nitrogen only occurs in traces, except in acid soils. In the same way the change:—nitrites→nitrates is more rapid than the change:—ammonium salts→nitrites. Hence, the proportion of nitrites is vanishingly small. Viewed as a whole, nitrification, the production of nitrates, is favoured by moisture, aeration, and warmth. It is inhibited by low temperature, drought, lack of aeration, and excessive acidity.

It remains to be noticed that fresh organic matter undergoes ammonification in the soil far more readily than humified organic matter, which is relatively resistant to biological attack by fungi and bacteria. It does not follow, however, that the addition of fresh organic matter to the soil always results in an immediate increase in the amount of ammoniacal or nitrate nitrogen. When organic matter that is poor in nitrogen undergoes bacterial decomposition, the organisms concerned themselves require available nitrogen, and there may thus be a decreased supply for the use of crops, with consequent depression of plant

growth. On the other hand, highly nitrogenous materials, such as dried blood or fish meal, are rapidly broken down, and soon provide available nitrogen for plant growth.

When large amounts of nitrate nitrogen are present in the soil, together with fresh organic matter, under intermittent anaerobic conditions, losses of nitrate may occur through *denitrification,* whereby free nitrogen is liberated. Such losses are unlikely to occur under ordinary conditions. Losses of nitrates also occur in drainage.

The nitrogen cycle in soils is represented diagrammatically in *Fig.* 4.

I have written at some length about soil organic matter because a right understanding of it lies at the heart of some of the most important problems of the soil. One of the chief aims of a rational system of land utilization should be the maintenance of the organic matter status. We have seen how the nitrogen supply to plants is intimately connected with the decomposition of organic matter in the soil. But humus has a wider significance. It is a constituent of the colloidal complex, which acts as the reservoir of bases—lime, magnesia, potash, etc., required for plant nutrition. Humus probably plays a part also in the phosphorus and sulphur nutrition of plants.

The part played by humus in the physical properties of soils is scarcely less important. In the first place it contributes greatly to the water-

holding capacity of soils. One of the principal defects of light, sandy soils is their pôor water-holding capacity. This may be increased by addition of organic matter to build up the humus. But humus also affects other physical properties of soils. A supply of humus, rich in lime, the so-called mild humus, promotes the development of that most desirable crumb structure of

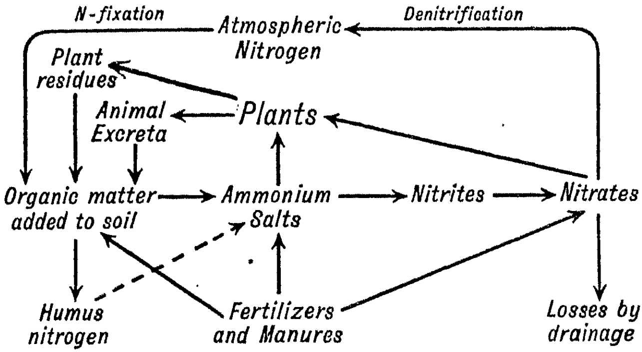


FIG. 4. The nitrogen cycle in soils.

which I have already spoken. It can thus correct the over-looseness and instability of sandy soils, and also make heavy clay soils more friable and, therefore, more easily workable. The favourable effect of humus can be well seen in old garden soils, to which I alluded at the beginning of this letter. Even in a clay country, old garden soils will be found to have a manageable tilth, although adjacent field soils may alternate between stickiness when wet, and the formation of

hard clods when dry. Well may a character in "Garden Rubbish"* say that "All really grim gardeners should possess a keen sense of HUMUS." A keen sense of HUMUS is as necessary for the agriculturist.

Ever yours,

G. W. R.

* "Garden Rubbish," by Yeatman and Sellars, who also gave us "1066 and All That."

Letter V

STRUCTURE AND TILTH

My dear Stapledon,

You may remember that I referred in an earlier letter to the porous nature of soil, and I said that the pore-space in soils was somewhere about 50%, subject, of course, to considerable variations, which we shall have to discuss in this letter. You will remember, of course, that soil is made up of particles of varying size, and that if all these particles were packed together in the closest possible manner the pore-space would be very small indeed. I can illustrate this by a jig-saw puzzle. If you spread all the pieces at random on a table, pushing them as close together as possible without making the picture, there will be a considerable proportion of uncovered table in between the pieces. But if you solve the puzzle, you will have no such spaces between the pieces, for they will all fit together. So, theoretically, if we could solve the three-dimensional jig-saw of the particles of a soil, we might get practically no pore-space at all between the particles.

Even if the particles were existing independently, we should always get some pore-space within the soil, because the three-dimensional jig-saw would never be solved. But actually we find that soil particles are more or less aggregated or clumped together to form compound particles or crumbs. Now, the more developed is this crumb structure, the greater will be the pore-space, because not only are there the bigger spaces between the crumbs, but the crumbs themselves are porous.

The formation of soil crumbs depends on the presence in the soil of the clay-humus complex or soil-colloid, which acts as a kind of cement, sticking the soil particles together. If the soil contains very little colloid material, then there will be very little crumb formation. This is the case in very light sandy soils, and we find that the pore-space in such soils is very low, sometimes going down to as little as 30%.

In a non-colloidal soil, not only will the pore-space be small, but it will not vary greatly. If, for example, you pour some coarse sand into a measuring cylinder, it will settle down very little on tapping or pressure. The case is quite different where the crumb structure is strongly developed. If you were to put some mellow garden soil into a cylinder, you would find it possible to compress it considerably by tapping and tamping. But even when it could not be compressed any more its pore-space would still be greater than that of the coarse sand.

Now, well developed crumb structure in a soil is most emphatically a Good Thing, for it is what the farmer means by *tilth*. In the first place, it favours the good aeration that is so necessary for the health of the soil and for the growth of plants. Secondly, it renders the soil permeable to water movements. This means that rain falling on it is rapidly absorbed, as by a sponge, any excess over that needed for saturating the surface soil being passed on to lower levels and ultimately to the drainage. There is thus no fear of water being held up and flowing over the surface, carrying valuable top-soil with it. Thirdly, the crumb structure tends towards stability against erosion by wind action during drought, for the finer particles, instead of being free to be blown about, are anchored down in the compound aggregates that are too bulky to be affected by wind. Finally, the crumb structure favours tillage operations, particularly in clay soils. But I shall have more to say of clay soils later.

What are the conditions favouring the development of this desirable crumb structure? In the first place, colloidal material must be present to act as a binding agent. But this condition needs some qualification. If the colloidal material is low in humus, *i.e.*, if it consists mainly of colloidal clay, the aggregation can result in the formation of hard intractable clods. This is particularly the case if lime is deficient. The worst state of affairs, however, is where the clay is

strongly alkaline, with sodium as the principal combined base, a condition unlikely to obtain under British conditions. On the other hand, where the clay contains a considerable proportion of lime it tends to have a better structure.

The most desirable type of colloidal material is that which contains a good proportion of humus rich in lime. In such cases, there is sufficient cementing action to give a fine crumb structure, whilst on the other hand there is no tendency to the formation of hard clods. The famous black earths of Russia and the N. American prairie soils, when just broken up, are of this type. A similar case is that of the Indian black cotton soils, which, although containing high proportions of clay, crumble down so readily on drying that they are said to plough themselves. I have also noticed the same effect in some of the calcareous clays of the Lower Lias formation, which readily fall down to a granular tilth on drying.

It would seem that the presence of a certain amount of fresh organic matter helps to give a good structure. If you shake out the soil from a mass of roots, for example, in a box of seedlings, you will see that it has a fine crumb structure. You will see the same thing in the turfy soil at the surface of pasture land, particularly if it is well supplied with lime. A contributory factor to the production of a good crumb structure is frost action, which has a very beneficial action on clay soils. Indeed some clay soils are scarcely manageable at all under tillage unless they have

experienced frost during the winter months. Summer drought often helps to improve the structure of heavy soils.

Having considered the factors which go to promote good structure we must now see how structure can be destroyed. If organic matter and lime can promote good structure, loss of these constituents must operate adversely, and this is indeed the case. Virgin soils, which originally contain enough organic matter to ensure crumb structure, when brought under continuous arable cultivation, rapidly lose organic matter by oxidative decomposition. If they are heavy soils the loss of structure or " fibre " becomes apparent by increasing difficulty of cultivation. But what is equally serious, and this applies to all types of soil, is that they become less permeable to the percolation of water: if there is heavy rainfall waterlogging takes place and surface run-off occurs. The soil, now broken down from its stable structure, is readily washed away and serious erosion may occur. This has been the history of millions of acres in North America and in the tropics, where the fertile top-soil has been removed and the raw sub-soil exposed. The sub-soil is even less permeable to rainfall and erosion goes on at an increasing pace. Not less serious is the liability to removal of fine material by wind action in drought, as shown by the appalling dust storms that have damaged and destroyed vast areas in the western regions of the United States and Canada.

A contributory cause to loss of structure is loss of lime. When soils are brought from virgin conditions into cultivation, a state of equilibrium is replaced by one in which lime is continually being lost from the soil. Even under the settled conditions of British agriculture this loss of lime plays its part in soil deterioration by rendering possible a deterioration in structure.

The moral of all this is that in any system of land utilization, attention must be paid to the maintenance both of the organic matter and the lime status. There are good reasons for this policy other than the maintenance of structure, but I shall deal with them in another letter.

I shall devote the remainder of this letter to some remarks on the tillage of clay soils. Actually, I suppose, nobody can know more about the behaviour of a particular soil than the farmer who has managed it for years. He knows by experience when it is suitable for the different operations of tillage. The heavier the soil the more necessary it is to catch it just at the right time.

In order to get some insight into the philosophy underlying the problems of clay soils, let us take a small handful of clay. If we mix it with a suitable amount of water, we shall find that the paste is plastic. It can be kneaded and moulded like putty or dough. If we add still more water, the paste will eventually become a stiff cream and behave like a liquid. It is possible by laboratory methods to determine fairly accu-

rately the point at which the clay-water paste changes from the plastic to the liquid state. This is called the *upper limit of plasticity*. If, on the other hand, we add more dry clay to our plastic paste, we find that it becomes increasingly difficult to mould and eventually we reach a point at which it simply breaks up or crumbles when we try to work it. This might be called the *lower limit of plasticity*. To give you a numerical example, I have in my laboratory a sample of London Clay that is plastic when mixed with more than 30% but less than 50% of water. When less than 30% of water is present, it crumbles down on being moulded; when more than 50% of water is present, it is no longer plastic but behaves as a stiff (viscous) liquid.

Now if we try to work a clay soil when it has enough moisture present to be plastic, we simply "paste" it. So that the lowest moisture content at which the soil is plastic really represents the highest moisture content at which the soil can be worked. If it is drier than this, it will crumble as our clay paste did when we tried to mould it with insufficient water to render it plastic.

Now let us look at the question from another angle. Let us suppose that our clay soil has been ploughed and that it is lying in big clods, as clay soils so often do if they have been ploughed rather too wet and if no frost has occurred to break down the clods. You have probably walked over a field many a time and kicked at the clods to try their hardness and you have probably

noticed that the drier the clods, the more difficult it is to break them down. With very heavy clay soils, clods may become so hard on drying out that neither the harrow nor the roller will crumble them. We are now up against another property of clay soils, namely, *cohesion*. The drier the soil, the more cohesive it becomes. If the farmer lets his clay soil get too dry, it becomes so cohesive that his implements cannot deal with it, and he must wait until a shower of rain improves matters. The effect of rain on the dry clods is two-fold. By moistening them it diminishes cohesion and also, since clay swells on being wetted, it tends to disrupt them.

So you will see that the great difficulty of clay soils is that they may be either so wet as to be plastic or so dry as to be too cohesive. And this means that the farmer has got to be very wary in choosing the right moment for his tillage operations.

A well-developed crumb structure, or the conditions necessary for producing such a structure, will help in the management of clay soils by facilitating the breaking down of clods, in other words by diminishing cohesion. Good organic matter and lime status in a soil will minimize the difficulties of its cultivation by increasing the range of moisture content over which it can be worked. If we must cultivate our clay soils let us see to it that the anxieties are diminished as much as possible by keeping up our organic matter and lime. Farmyard manure and grass

leys will take care of our organic matter; and as for lime, have we not the Government subsidy?

Ever yours,

G. W. R.

LETTER VI

THE SOIL PROFILE

MY DEAR STAPLEDON,

I have already enunciated the soil profile theme, and in this letter I shall try to develop it further. But before proceeding to this task, I must invite your attention to a few simple facts of geology, for geology underlies pedology, and our study of soils is grounded in the study of the rocks from which they are developed.

The outlines of the cycle of weathering are known to you. The rocks of which the land is made are continually undergoing destruction by weathering, and the products of weathering are eventually carried by rivers to be deposited as sediments on the sea floor, where they accumulate and, in time, become altered by pressure, and possibly by heat, to form rocks. Great millennial changes alter the distribution of land and sea, and the rocks formed below the sea are slowly lifted up to form land, when they again become exposed to weathering and denudation, whilst that which was land sinks below the sea to receive the burden of new sediments. Not all rocks have originated as sediments, for there is the great class of igneous rocks formed by the

solidification of molten material. With them we may group metamorphic rocks, which have been subjected to great heat, whereby they come to resemble in their constitution the igneous rocks. Both may be referred to as crystalline rocks. From the standpoint of soil formation we must distinguish clearly between igneous and sedimentary rocks. Igneous rocks, with which we may group rocks formed by heat-metamorphism, consist entirely of minerals which have crystallized out from the molten or semi-molten state. Sedimentary rocks, and with them we may classify limestones (formed mainly of the calcareous remains of marine organisms), also contain minerals derived from earlier rocks and ultimately from igneous rocks, but they also contain material which has resulted from the chemical decomposition of their antecedent rocks. Inasmuch as soils originate from the decomposition of rocks by weathering, the formation of soils from sedimentary rocks is really the resumption of a process that has already gone on in the original formation of these rocks. Only in the formation of soil from igneous or metamorphic rocks is the process of a primary character. I shall have occasion to qualify this statement somewhat at a later point, but I think you will see that there is a difference between soil formation from a crystalline rock such as granite or mica schist and that from a rock such as the London Clay or Gault. I will only add that many sedimentary rocks, such as the grits, shales, and mudstones of the

older formations in Wales, occupy an intermediate position. Although they are sedimentary rocks, they have in some cases been subjected to such a degree of heat metamorphism as to acquire some of the characters of crystalline rocks.

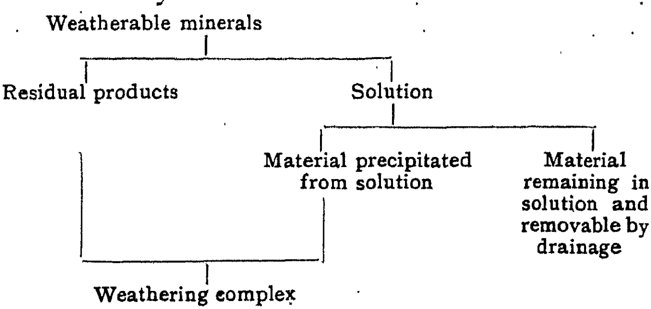
Let us now look at rock weathering more closely. Rocks exposed to atmospheric influences undergo weathering. This can be seen in the stones of ancient buildings and in churchyards. Indeed, a churchyard is an excellent place for the study of rock weathering because not only are the memorials of varying age but also of different materials. We may see the rapid weathering of sandstone and the slow weathering of slate, and we may see how polishing, by preventing the lodgement of moisture, to some extent protects against decay.

We can distinguish two types of weathering, namely (*a*) physical or mechanical and (*b*) chemical. In physical or mechanical weathering, no chemical changes are involved but merely mechanical disintegration, the same kind of change that would occur if the rock were simply crushed down to fragments. Physical weathering can take place in a number of ways, by alternate expansion and contraction consequent on temperature changes, by frost action, by the abrading action of glaciers, by running water, or even by the blast of sand blown by wind. They can be studied in more detail in any textbook of geology.

In chemical weathering, more profound changes occur. Minerals present in the weather-

ing rock are decomposed and new substances are formed. Here we must distinguish between weatherable and unweatherable minerals. The commonest unweatherable mineral is quartz, which survives unchanged, except for physical comminution, through successive weathering cycles. Other unweatherable minerals are magnetite and certain other oxides of iron and titanium.

The most important group of weatherable minerals is the felspars. Other groups of weatherable minerals are the micas and the ferro-magnesian minerals, *e.g.*, hornblende and olivine. This is not a treatise on geo-chemistry and I shall not attempt an exposition of the processes whereby felspars, micas, and ferro-magnesian minerals undergo chemical decomposition with the formation of new products. These decompositions, in which oxidation of ferrous to ferric iron plays a part, are due to the chemical attack of water, reinforced by the presence of carbon dioxide in solution. We may represent it schematically as follows:—



The end-products of chemical weathering are therefore: (*a*) the so-called weathering complex, which may consist partly of residual and partly of precipitation products and (*b*) material finally remaining in solution, which is removed in the drainage from the seat of weathering and either accumulates at lower levels (in arid climates) or passes into the river system (in humid climates) and ultimately to the sea. The materials carried in solution by rivers thus represent the mobile products of weathering.

The weathering complex varies in composition under different conditions. Regarding the process of chemical weathering as a break-down or degradation from the original minerals, different stages may be distinguished, varying from a type of weathering complex comparatively rich in silica, formed under arid and semi-arid conditions, to the end-product consisting mainly of alumina and ferric oxide to which weathering tends under humid tropical conditions.

Physical and chemical weathering can proceed at the same time, but we may regard physical weathering as facilitating chemical weathering, since by breaking down rocks it exposes fresh surfaces to chemical attack. Chemical weathering is at minimum under desert conditions, owing to absence of moisture, and under polar and alpine conditions owing to low temperature. It is most intense under humid tropical conditions. It is not uncommon in the tropics to find one hundred feet or more of material, weathered in place, over-

lying its parent rock. In temperate climates, the zone of weathering is much shallower. In regions which have undergone Pleistocene glaciation, the extent of chemical weathering is restricted also by the relatively short time during which chemical weathering has proceeded since the last ice retreat.

We must regard weathering, physical and chemical, as essentially a geological process, fulfilled, it is true, in the superficial layers of the earth's crust in close relationship with the soil and its processes. The development of the soil profile must be regarded as superposed on the geological process of rock weathering. Such a superposition is evident where the soil profile is developed from unconsolidated sediments consisting of the re-sorted products of an earlier cycle of weathering, as for example Tertiary and Recent deposits, which retain essentially their character as subaqueous deposits. It is evident also where the profile is developed in the superficial layers of a deep mantle of material resulting from the weathering in place of rocks under tropical conditions. Where the zone of weathering is shallower, as in the case of British soils derived in place from hard rocks, we may presume that profile development is so closely superposed on weathering as to proceed almost *pari passu*.

The way is now clear for me to discuss the actual processes whereby the soil profile is developed, in other words the processes whereby the weathered rock material is differentiated into the horizons characteristic of an actual soil.

The factors concerned in this differentiation are:—(1) the presence of a cover of vegetation, from the residues of which soil organic matter or humus is formed, whilst carbon dioxide is liberated from the biological decompositions involved and from the respiration of roots; and (2) the water conditions in the soil, which determine (*a*) the translocation of material from horizon to horizon in the profile, and (*b*) the occurrence of oxidation or reduction, the latter condition prevailing where oxygen is excluded from the soil by waterlogging.

In my last letter, I dealt at length with the subject of humus and it only remains to notice that the humus profile depends on the character of the native vegetation and also on the relative intensity of the oxidative and the humifying processes. For example, under semi-humid climates with tall grass vegetation in mid-latitudes (N. America) there is a fairly uniform and high content of dark humus of high lime-status (mild humus) to a depth of two or three feet, below which the humus content sharply diminishes; in cool humid climates under coniferous forest there is a marked accumulation of peaty humus in the upper part of the profile succeeded by an horizon of low humus content, which in turn may be succeeded by a narrow horizon in which humus again increases. Other examples will be given when some typical profiles are described.

The effects of water conditions on profile development must be considered in more detail.

They depend on the relative intensity of rainfall and evaporation and also on the occurrence of ground-water or an impervious horizon near the surface.

Where rainfall predominates over evaporation (including transpiration) the net result of each year's exchanges will be a gain of water to the soil profile. This can only be disposed of by downward percolation and the soil is thus subjected to a downward washing or *leaching*, which, however, may be interrupted during periods of drought. This downward washing or leaching has the effect of removing material either mechanically or chemically from the surface layers. Material thus removed may be re-deposited at lower levels or may even pass away from the profile into the drainage. The whole process is termed *eluviation* and the surface horizon from which materials are removed is termed the *eluviated* or *A-horizon*. Below it is the *illuvial horizon* or *B-horizon*. Both the A- and the B-horizons may be further subdivided on the basis of subsidiary characters. Below the B-horizon is the *C-horizon*, which is the parent material from which the profile has become differentiated.

I said above that eluviation might be mechanical or chemical. Mechanical eluviation occurs when, owing to loss of crumb structure, fine material becomes mobile and is washed down in the profile to be deposited at lower levels. The increase in clay content in passing from topsoil to subsoil can be noticed in most profiles, but in

some cases there may be a strong differentiation into a coarse textured A-horizon and a fine textured B-horizon, which may form a clay pan of sufficient development to hold up percolation. Some of the best examples of such mechanical eluviation are found in the S.E. United States.

In chemical eluviation, material is transported in solution. In the first place there is the solution and downward transport of the bases, lime, magnesia, potash, and soda, mainly in the form of bicarbonates but to some extent as sulphates and chlorides. In the completely leached profiles of humid climates, these are washed out and lost in the drainage; the profile falls in base-status and becomes acid until the loss in bases is just balanced by gains from the weathering of minerals in the soil. In drier climates, where leaching is incomplete, deposition of carbonates and sulphates may take place at the lower limit of leaching.

When the base-status of the soil is lowered by leaching out of bases, the clay complex may undergo decomposition. In the initial stages, this may result simply in the liberation of free silicic acid, alumina, and ferric oxide, such a change being betokened by the yellowish, orange, or brown colour of hydrated ferric oxide. Where the removal of bases is more accentuated, ferric oxide, and in extreme cases, alumina, may pass into solution associated with humic acids, and be removed from the upper horizons, which thereby acquire a bleached appearance. Deposition of

ferric oxide and alumina occurs at lower levels, giving a yellowish-brown sesquioxide B-horizon, which in extreme cases may be hardened to a pan. Deposition of humus may also occur, giving a humus B-horizon. This intense eluviation occurs only in humid climates where the surface consists of very acid raw humus, the residues of coniferous or heath vegetation.

Where evaporation predominates over rainfall, in arid and semi-arid climates, the type of eluviation is different, for the rainfall moistens the profile only to a limited depth. During drought, there is an almost complete drying out of the profile. Eluviation is therefore incomplete and there is a tendency for mobile materials, notably calcium carbonate and gypsum, to be deposited in the soil profile.

Another type of profile development is that associated with drainage impedance and the occurrence of ground-water. Here we can distinguish a zone of eluviation and a zone in which, owing to fluctuation in ground-water level, oxidation and reduction alternate, producing a characteristic mottling and staining due to precipitation of iron oxides. This horizon is called a *gley-horizon* or G-horizon. Below the gley-horizon in the zone of continuous saturation, conditions are permanently reducing and the horizons have a grey or bluish-grey colour owing to the presence of ferrous compounds.

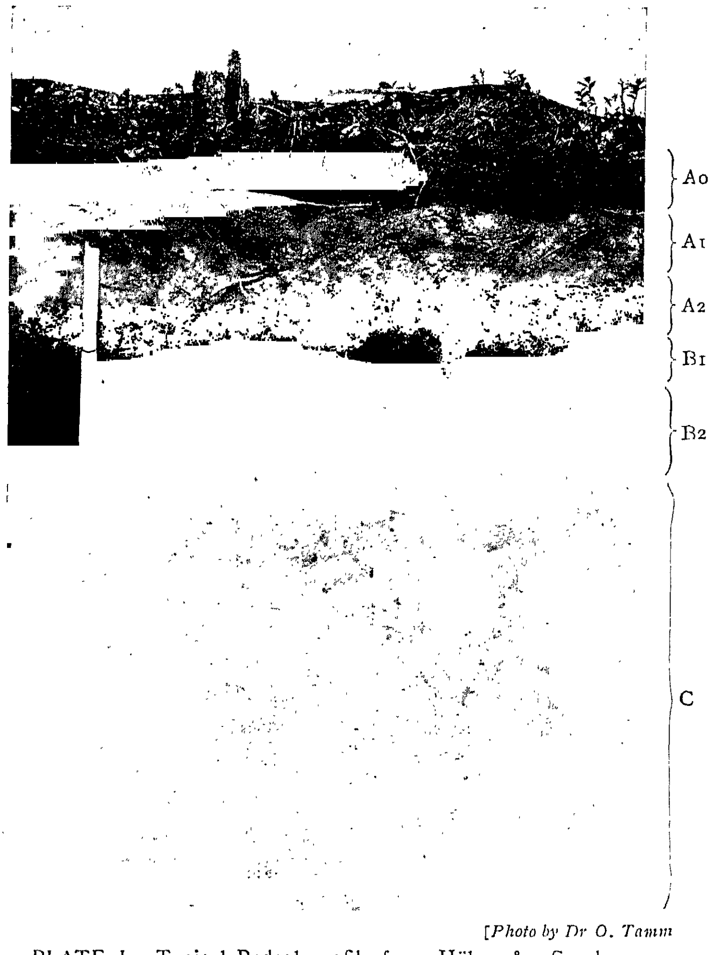
As I said in an earlier letter, when introducing the subject, the soil profile is a record of the

history of the soil. Sometimes it is a record which can readily be interpreted. Often it may be more readily compared to a palimpsest. Most of our British profiles are of this kind, bearing the imprint of their recent history superimposed on the more or less obliterated characters of their primitive state.

And now I cannot do better than describe to you a typical soil profile, which you will see in the accompanying photograph (*Plate* I). It was taken by my friend Dr. Olof Tamm, of the Swedish Forest Research Institute. It has appeared in one of his publications and I thought it showed so well the characters of the type of profile known as the *podsol,** that I asked his permission, which was graciously given, to use it.

This profile occurs at Hökensås, near the south end of Lake Vettern, under Scots Pine (*Pinus sylvestris*) forest with a ground vegetation of Bilberry (*Vaccinium myrtillus*, and *V. vitis idæa*), together with mosses and some ling (*Calluna vulgaris*) and lichens. The mean annual rainfall is 650—700 mm., whilst the mean temperature varies from $-3{\cdot}5^{\circ}$ C. in January to 15° C. in July. The drainage is free. The parent material from which the profile is developed is a quartzose sand poor in basic constituents and clay. The depth of the profile can be judged from the small rule stuck in at the top. This is about a foot long. Now we can notice the several horizons; they are distinguished by the letters at the right hand side of the picture.

* A word of Russian origin meaning an ashen coloured soil.



[*Photo by Dr O. Tamm*

PLATE I.—Typical Podsol profile from Hökensås, Sweden.

[*To face page 68*

A_0 is the horizon of raw humus consisting of the decomposed and decomposing remains of the leaf fall and the residues of the ground vegetation. It is dark in colour and very spongy.

A_1 is bleached sand mixed with amorphous humus.

A_2 is bleached sand containing very little humus. Dr. Tamm does not mention it in his description, but if this profile resembles similar profiles that I have examined, both this horizon and the one above it show a loose dusty structure when dry.

B_1 is a dark rusty-brown horizon somewhat hardened to form a kind of pan. It contains more humus than the horizon above it.

B_2 is a rusty-coloured horizon, not so indurated or so rich in humus as B_1. The distinction in colour between this and the preceding horizon cannot be clearly shown in a photograph.

C is the raw sand, which is the parent material out of which the profile is developed. It is lighter in colour than B_2 and probably less compact. The wave-like markings in the picture are due to the implement used in making the excavation and not to the natural structure.

Now the characters of this profile are determined by the following circumstances:—

(1) The humid and cool climate. Rainfall predominates over evaporation and there is thus a complete washing or leaching of the profile. Also the comparatively low temperatures do not favour the rapid oxidation of leaf-fall and other plant residues.

(2) The low mineral status of the parent material (quartz sand) and

(3) The vegetation, which is adapted to this low mineral status and whose residues accumulate as an acid peaty humus layer at the surface.

Now when humus is very poor in mineral matter it tends to become unstable and go into solution, giving a weak acid solution. It is this weak humic acid solution that leaches down through the soil profile. On its way down, it dissolves ferric oxide and possibly alumina from the clay complex. This gives the bleached appearance to the A_1- and the A_2-horizons.

But this leaching out of humus and ferric oxide (with some alumina) does not go on right down the profile, for in the B_1-horizon most of the humus and some of the ferric oxide is precipitated. We are not quite sure how this precipitation takes place. It seems probable that it takes place during the summer when the profile is drying out, in which case the material deposited in the B-horizons sinks deeply in the profile and then rises again to be precipitated. However this may happen, we get the B_1-horizon dark-coloured through deposition of humus and the B_2-horizon bright rust-coloured owing to deposition of ferric oxide.

The B-horizon has a more compact structure than the A-horizon; this is notably the case in the B_1, which forms a kind of pan. The B_2-horizon is fairly compact and more granular than the A-horizons.

So now you have an example of what is meant by a soil profile. In a later communication, I shall review briefly some of the principal kinds of soil profiles encountered in this country and abroad. Let me say again, and I shall repeat it in later letters, that the soil profile bears imprinted on it the history of the soil. If we could only read it aright we could reconstruct that history, just as an archæologist can reconstruct the history of a site like that of Troy from the successive strata down to the unaltered geological material.

Ever yours,

G. W. R.

LETTER VII

SOME TYPICAL SOILS

MY DEAR STAPLEDON,

In my last letter, I described in some detail a soil profile. This kind of profile, the so-called podsol, represents an important group of soils of wide occurrence throughout temperate and cool humid regions. It is developed wherever free leaching takes place in association with a surface layer of peaty humus. In very humid and cool climates, it tends to occur on all types of parent material. In warmer and drier climates, it is confined to parent materials such as quartzose sands and grits, which are poor in basic materials. It does not occur in semi-arid and arid climates, whilst in the tropics it is only found on highly quartzose sands under constantly high rainfall. The associated vegetation in temperate and cool climates is coniferous forest or heath.

The distinguishing features of the podsol profile are (*a*) the peaty humus layer, (*b*) the bleached A-horizon, and (*c*) the accumulation of hydrated ferric oxide in the B-horizon. In extreme cases there is also a layer of humus deposition in the B-horizon. Alumina also may accumulate to

some extent in the B-horizon. Ferric oxide accumulation in the B-horizon is betokened by orange or rusty-brown colours, humus accumulation by dark smoky-brown colours. Whilst the A-horizon is light-textured and loose in structure, the B-horizon is heavier and more compact and may even form a pan in its upper portion.

There are many variants of the podsol profile. Frequently there is a certain truncation or removal of the upper horizons by erosion and the original B-horizon may form the surface soil. In other cases, the bleached horizon is masked by humus and the profile shows a dark horizon directly overlying an orange or rusty-brown B-horizon.

Podsolic soils are most characteristically developed in cool or cool-temperate humid climates. They may occur under high rainfall even in warmer climates where the parent material is poor in bases, as, for example, in the Dutch East Indies, where soils having all the essential features of a podsol have been found developed on poor quartzose sands under high rainfall.

Podsolic soils represent extremely acid conditions with intense leaching. With their extremely low base-status and lack of crumb structure, podsols are among the poorest varieties of soil. In order that they may be brought into yielding, liberal initial dressings of lime, phosphate, and potash are required; and constant attention is needed to prevent reversion.

Akin to the podsolic soils are a group of soils variously known as *brown earths*, *brown forest soils*, or *grey-brown podsolic soils*. These are developed where leaching is less intense and soil conditions less acid, *i.e.*, in warmer and drier climates or on less acid parent materials. The natural vegetation is deciduous forest or scrub. The humus layer is less strongly developed and the humus is of the " mild " type. There is no marked bleaching, although it is sometimes possible in the laboratory, if the humus is destroyed by oxidation with hydrogen peroxide, to distinguish a lighter shade in the surface soil. Removal of ferric oxide from the A- and deposition in the B-horizon occurs only slightly, if at all. At the same time, the profile shows brown or orange-brown colours owing to the presence of free hydrated ferric oxide. There may be a certain amount of mechanical eluviation resulting in a certain differentiation into a light-textured A, and a heavier-textured B-horizon. The granular or crumb structure of the surface soil is in contrast with the loose structure of the A-horizon in podsols. Although the profile is less acid than the podsol, leaching is sufficient to remove any calcium carbonate from the profile.

Agriculturally the brown earths are considerably better than the podsols. Most of the freely-drained soils of southern and eastern Britain, except the calcareous soils, belong to the brown earth group. Well-drained lowland soils in Wales show transitions from the brown earths to

the podsolic soils. Many of the upland agricultural soils of Wales might be described as feebly podsolic. It is possible that some of the brown earths of the present day may represent podsols that have been changed by agricultural use.

Brown earths are typically developed in temperate climates, but may occur in Continental Europe as far north as southern Sweden. As in the case of the podsols, parent material plays an important part. Thus, whilst the typical well-drained soils of southern and eastern England are brown earths, where the parent material is quartzose sand, poor in basic materials, podsols are developed. On the other hand, with basic parent materials, brown earths may occur even in such a cold climate as that of Iceland. There are, however, differences between brown earths of high and mid-latitudes. With increase in mean annual temperature, oxidation of plant residues becomes more intense and the organic matter status tends to fall. The colour of the mineral portion of the soil also tends to become lighter and more vivid.

There is an important group of soils developed typically in North America, but which may occur also in other parts of the world. These are the *prairie soils,* found naturally under tall grass vegetation with drier climatic conditions than those of the forest regions. The absence of forest may not be directly due to the relative dryness of the climate but rather to the check on forest development by grazing of wild animals, for, since

these regions have been colonized, neglected land has gone to forest or scrub.

Prairie soils show profiles with deep surface horizons of dark granular soil rich in humus. Although the climate is sufficiently wet for calcium carbonate to be completely leached from the profile, the leaching is not so intense that the profile becomes markedly acid, and prairie soils have therefore a fairly high base-status. The mineral colour of the soil is largely masked by the humus, but even when humus is removed, the colour of the mineral portion of the soil is greyer than that of brown earths. This is owing to the type of clay complex or weathering complex, which is more siliceous than that of the brown earths and does not contain free ferric oxide in sufficient amount to give the typical brown or orange-brown colour found in soils of the brown earth group. Prairie soils when brought into cultivation are even more productive than brown earths. I consider that the soils of our best old grasslands show considerable resemblance to the prairie soils.

In the humid tropics, leached soils with free drainage are generally of a bright red or orange-brown colour. They probably have affinities with the brown earths, but they are usually poorer in organic matter owing to the rapidity of oxidation. They are also richer in sesquioxides. Indeed, in extreme cases, the mineral portion of the soil may be mainly hydrated alumina and ferric oxide. Such a soil is called a laterite. Tropical soils are more highly weathered than soils of tem-

perate regions derived from similar parent materials: it is not uncommon to find eighty or one hundred feet of weathered material overlying the parent rock. The tendency has been to reckon all this depth of material as belonging to the soil profile, but it would probably be more correct to regard it as the parent material of the soil and regard the top few feet as the actual soil profile.

I have hitherto spoken of soils in which the profile is completely leached. There is another great class of soils in which leaching is limited by the dryness of the climate. Where evaporation predominates over rainfall, the state of affairs in the soil profile may be likened to that of a flower pot containing soil and watered so scantily that water never flows out of the drainage hole at the bottom. The soil is moistened to a certain depth and then dries out. This is the position in steppe, short-grass prairie, desert-scrub, and desert soils.

The most important group of soils in this class is the *tshernosem* or *black earth* group.* These soils occur typically in south-eastern Europe and in the high plains of the United States. The climate, though dry, yields sufficient moisture to support a natural vegetation of grass and herbaceous plants in close cover. Carbonates are leached from the surface soil, but the base-status remains high. A constant feature is the presence of a zone of calcium carbonate precipitation at two to five feet from the surface.

* Tshernosem is the Russian term for black earth. It is also transliterated as *chernozem*.

There is frequently an accumulation of gypsum below the calcium carbonate horizon. The calcium carbonate occurs, sometimes as nodules or concretions, sometimes as a filamentous deposit like the mycelium of a fungus.

The organic matter status of the black earths is fairly high and, because of the high base-status, the humus is dark in colour, so that these soils appear black when wet, even when only moderate proportions of humus are present. However, in some Russian black earths the humus content may run up to 16%. The layer showing the dark humus colour varies from 1½ to 3 feet in depth, and there is often an abrupt colour change to the grey-brown or grey material below. The warm brown colours due to free ferric oxide are wanting, and the clay complex is of a siliceous type similar to that of the prairie soils. Black earths have a fine granular structure and present little or no difficulty in cultivation. If the soil becomes impoverished in humus by long-continued exhaustive cultivation, the good granular structure may be lost. The soil is then subject to wind erosion during drought: witness the appalling dust storms of recent years in North America.

Apart from their liability to drought, the soils of this group are well suited for arable culture and, in particular, for large-scale wheat growing. Some of the most important wheat areas of the world are on these soils. If exhaustively cropped, they may deteriorate and suffer both impoverishment in plant food and loss of the granular structure that renders them so easy to cultivate.

In climates drier than those under which black earths occur, similar profiles are found, but the organic matter content decreases and the colour of the soil becomes lighter, passing finally to the grey-brown or grey of desert soils. Drier climatic conditions are also associated with more marked development of the horizon of calcium carbonate accumulation, which also tends to occur nearer the surface, so that in desert soils it is close to the surface and may actually be at the surface when the overlying soil is removed by wind erosion.

I now come to the third great class of soils, namely those developed under conditions where leaching of the profile is impeded either by the presence of an impervious stratum or by the occurrence of ground-water near the surface. When such conditions obtain, the lower part of the profile is waterlogged and air is excluded. Owing to seasonal variations in wetness, there are fluctuations in this waterlogged zone. During the wet season it will approach the surface, whilst in drier weather it will sink. You have probably noticed that water in ditches stands nearer the surface in winter than in summer. We thus have at the bottom of the profile a permanently waterlogged zone, from which air is always excluded and in which conditions are always reducing (in the chemical sense), and a zone which is sometimes waterlogged and sometimes aerated, in which oxidizing and reducing conditions alternate. There may also be a surface

zone where aeration is always sufficient to ensure oxidizing conditions. Under chemically reducing conditions, iron compounds tend to go into the ferrous condition and the soil colours are grey or bluish-grey. In the zone where conditions alternate, the grey colour is relieved by streaks or mottlings of a rusty orange-brown or yellow colour, betokening the presence of hydrated ferric oxide. This horizon of alternating oxidizing and reducing conditions is sometimes called a "*gley*" horizon and soils that show such an horizon are termed *gley soils*. In addition to deposits of hydrated ferric oxide we may also find manganese dioxide, gypsum, and even calcium carbonate deposited.

The constant marks of soils with impeded leaching, which of course means impeded drainage, are generally greyish soil colours, with rusty, yellow, or orange-brown mottling or streaking in the so-called gley-horizon. In addition to the mottling and streaking, one can generally notice rusty markings along root channels in clay pastures. These marks enable us to spot bad drainage conditions even when the soil is examined in the dry state.

Soils of this class are, as might be expected, generally wet. In the natural state they occur under swamp, marsh, or wet woodland vegetation. Among our agricultural lands they include considerable areas of grassland. At their best and with good management, they produce excellent summer pasture, but at their worst they carry

almost pure stands of rushes. Artificial drainage brought large areas of impeded drainage soils into high productivity. Much of this land had deteriorated in pre-war years owing to neglect. In many cases cleaning of ditches has been sufficient to restore drainage.

Gley soils, on account of their tendency to winter wetness and their generally heavy texture, are rather grassland than arable soils. Yet there are also many instances of sandy gley soils where the drainage impedance is due to a regional water-table. If this can be controlled artificially, the resulting soil may be highly productive under good management. Some excellent horticultural soils are in this category.

Podsols may undergo transformation into gley soils where the development of the B-horizon becomes so marked as to impede drainage. The resultant profile is termed a *gley-podsol* or *gley-podsolic soil.* Gleying is associated with an increase of peat development and a change in vegetation from the forest or heath type to the moorland type. Much of the *Nardus-Molinia* pasture in Wales was probably podsol in an earlier stage.

Peat soils are related to the gley soils. Indeed, many peat soils may be considered to have developed from gley soils, for constant wetness, with exclusion of air, not only favours plant growth but also the humification of plant residues, which accumulate in place. We may distinguish two great types of peat, namely the *fen* or

lacustrine peats and the *upland* or *moor peats*. Fen peat is formed from the residues of aquatic vegetation and, since these generally have a fairly high mineral status, the resulting peat is of a type that, when drained, can yield fertile soils as in the Fens. This generalization is not always applicable to our Welsh lacustrine peats. Where the peat has been formed from plants growing in a lake whose waters are very poor in dissolved minerals, its mineral status is correspondingly low and it will offer poor prospects for intensive utilization.

The upland and bog peats are formed from the residues of plants that grow in wet situations where the moisture contains very little mineral matter, as for example the surface water percolating down mountain slopes. In certain kinds of bog peats, the mineral status can be very low indeed, for the soil moisture has no connexion with the mineral subsoil. In very wet climates, peat can accumulate in almost any situation, for, the surface being continually moist, peat forming plants such as sphagnum moss and deergrass (*Scirpus*) establish themselves. In drier climates, the formation of peat is limited to basin-shaped areas or slopes maintained continually moist by surface water.

I do not propose to write at great length on peats. My own feeling is that, except for the fen peats, they offer poorer prospects of improvement than most of the other types of waste land. When these other types have been fully im-

proved, it may be time to consider the improvement of bog and upland peats.

I have not attempted, in this letter, to bring to your notice all the important varieties of soil profile. If I had attempted this I should have been obliged to include some important tropical soils and also those soils developed under the influence of sodium salts. I should also have felt it necessary to describe soils, such as the alluvial soils (or more correctly soils derived from alluvial material) which, though valuable from the economic standpoint, show little profile development, owing to their youth. But I should like you to think of soils as falling into three groups, namely, (*a*) the completely leached soils, including our podsols and brown earths; (*b*) the incompletely leached soils, including the black earths; and (*c*) the soils with impeded leaching, including the gley soils and peats.

Ever yours,

G. W. R.

Letter VIII

SOIL MOISTURE

My dear Stapledon,

About three centuries ago, Van Helmont carried out his famous experiment that appeared to prove that water was the "principle of vegetation." He set a willow shoot, weighing 5 lbs., in a barrel containing 200 lbs. of dry soil and, at the end of five years, obtained a willow tree weighing 169 lbs. 3 ozs. The loss in weight of the soil was a trifling two ounces, and the only material given during the period was pure water. Van Helmont knew nothing of the assimilation of carbon by green plants from the carbon dioxide of the air. That discovery was reserved for the next century and he appeared to be making a perfectly logical inference in asserting that plants obtained their aliment from water.

Now, although Van Helmont was misled by his ingenious experiment, it remains true that water is of the utmost importance for the growth of plants. As you know, for every part by weight of dry matter formed, from two hundred to one thousand parts by weight of water must be absorbed by the roots of plants. Of all the factors affecting plant growth, water-supply prob-

ably has the greatest weight in deciding the differences in crop-producing ability between one soil and another. Indeed, if the water-supplying power of a soil is satisfactory, the other requisites for plant growth are generally adequate for high production, because such soils have been found by experience to repay generous treatment and have been well manured and cultivated. Conversely, infertility or uncultivation are more often than not traceable to unsatisfactory water supply, including in this condition both excess and deficiency of moisture. No excuse is needed, therefore, for devoting a whole letter to the subject of soil moisture; because what the soil does with the rainfall that it receives determines what use crops growing on it will be able to make of the moisture given by the heavens.

In order to understand the differences in the way in which soils dispose of their rainfall we must distinguish two properties, namely, water-holding capacity and permeability to water movements. Soil as a material has the capacity for water retention, partly on account of its obvious porosity but still more on account of the presence in it of clay and humus, both of which have an enormous capacity for water retention. Indeed, the differences in water-holding capacity of soils are almost entirely due to their different contents of clay and humus. We should perhaps note that humus has a greater capacity for water retention than clay. Peaty soils can retain very large quantities of moisture.

It can be readily understood that soils differ in their capacity for retention of water. It is not so easy to give a quantitative expression to these differences. Obviously, the maximum water capacity of a soil is represented by the amount of interstitial space or pore-space present. In actual practice, water retention up to the full limit of the pore-space would only be found in completely waterlogged soils, or below the level of the ground-water or *water-table*. And before we go further I must explain what is meant by the water-table, because I shall have frequent occasion to refer to it.

Let us go and dig a hole in a piece of low-lying land near a stream. We shall find, before we get very deep, that we have reached water, and if we leave the hole that we have dug for a short time, water will fill in and stand within a short distance of the surface. Water tends to find its own level, and so if water is standing in the hole at, say, two feet below the surface of the land, it will tend to stand at that level within the neighbouring soil profile. The level of this subsoil water is called the water-table. Its distance from the surface varies. In uplands it may be very deep. Near rivers, ponds, or lakes it approaches nearer the surface, for the water-table is continuous with the adjoining free water surface. At the same place, the level of the water-table will vary with the season, rising in winter and falling in summer. Where impervious strata are present, high water-tables may occur, even

away from valley bottoms. In such cases, as for example in the Gault clay, it is possible on digging down to pass through a zone of complete saturation and find quite dry clay beneath. Such a water-table is sometimes termed a *perched* water-table.

Water-tables slope valleywards, so that they continually feed the river system. A spring is an outcrop of a water-table at the surface. The picture of the water-table in some of our Welsh uplands would probably be rather complicated. At one place it might lie deep down in the jointed rock, at another it might lie near the surface owing to the occurrence of a rock-basin or the accumulation of impervious subsoil in a hollow.

If we examine a soil profile down to the water-table we shall find great variations in the moisture picture at different seasons. At the water-table and immediately above it, the soil (or subsoil) is always completely saturated with water up to the limit of pore-space, but above this level, the amount of water present in the soil depends on the vicissitudes of rainfall, evaporation, and transpiration by plants.

Let us imagine the course of events in a typical soil profile. We will assume that it is fairly permeable to water movements and that the water-table lies about eight feet below the surface. Let us suppose that we are at the end of a dry summer, so that the upper part of the profile, at any rate, will be dried out. The

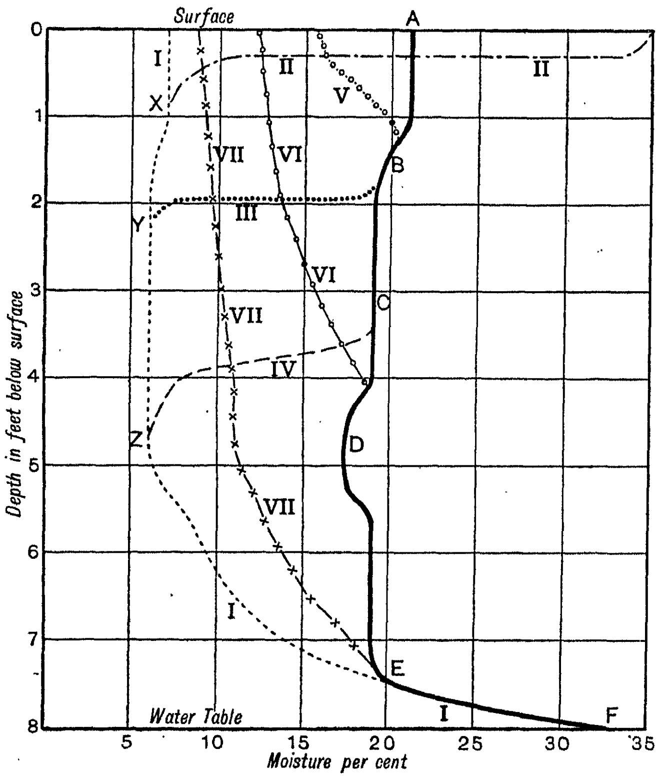


FIG. 5. Changes in moisture content of a soil profile during wetting and drying.

variations in moisture content down the profile can be represented by the curve I in the accompanying diagram (*Fig.* 5). Now let us call for a heavy downpour of rain, and consider what happens. The surface soil will become very wet and may even be temporarily waterlogged. The position can now be represented by curve II, which joins curve I at a short distance (X) below the surface. Now let us turn off the rain for a little, assuming for the moment that there is no loss from the surface by evaporation or transpiration. Moisture in the surface soil will percolate downwards, moistening the soil below, and this will go on until a state of equilibrium is reached, which may be represented by curve III, which again joins curve I at a point (Y) below that where curve II joined. The point to notice is that the added moisture does not distribute itself evenly throughout the profile, but that it simply saturates so much of the soil up to what is termed the *field capacity*. The final attainment of this equilibrium would be rather slow, but as this discussion is quite hypothetical, we can assume that sufficient time has elapsed. Having got our profile moistened up to the condition represented by curve III, we will suppose that a further downpour of rain occurs. Again there will be a supersaturation of the surface soil and subsequent adjustment leading to the saturation of a greater depth of soil. The position could then be represented by curve IV, which will be

coincident with curve III in its upper portion, and with curve I in its lower portion (below Z). With more rain, we may reach the state of affairs represented by the curve A B C D E F in which the whole profile is saturated up to field capacity. If this position has been reached, then any further rain will supersaturate the surface, but the excess moisture is successively passed on by downward percolation until it reaches the water-table and the moisture gradient A B C D E F is again restored.

There is thus for every soil profile a normal moisture gradient down to the water-table, representing equilibrium conditions. In actual practice, such a gradient scarcely ever obtains. During the wet season, there will generally be supersaturation in part or the whole of the profile, and more rain will probably fall before there has been time for equilibrium to be reached. On the other hand, even in the wet season, during intervals between rains, evaporation and the absorption of moisture by plant roots may temporarily reduce the moisture content of the surface soil below its field capacity. When dry weather sets in, or when evaporation and the use of water by plants exceed rainfall, the profile becomes drier. The losses affect the surface layers at first, but as these dry out losses occur from deeper layers, although at a slower rate. We might represent successive stages of drying out of our soil profile by curves V, VI, and VII, the lower portions

of which will coincide with the field capacity curve.*

We can imagine an ideal field capacity gradient for every soil profile. Like most ideals, it is rarely, if ever, attained, but it represents the kind of distribution towards which the soil moisture tends. It will be affected by the position of the water-table, which, of course, varies seasonally, even in the same soil, by the occurrence of the relatively impermeable layers, which slow down percolation, and by the character of the soil material itself.

I must enlarge somewhat on the effect of the soil material itself on field capacity. I said at the beginning of this letter that clay and humus were of great importance in the retention of water by soils. In a sample of coarse sand containing no clay or humus, water is held entirely in the form of thin films moistening the surface of the particles. Water retained by clay and humus is present in a state resembling that of water in a jelly. Such water is sometimes called imbibitional moisture, to distinguish it from moisture in external films. Clay can absorb more than its own volume, and humus many times its own volume of water.

The effect of clay and humus is reflected in the vertical variations in the field capacity in a soil

* The course of events has, of course, been greatly simplified in the present treatment. In practice, the level of the water-table would stand highest at the end of the winter and lowest at the end of the summer, with consequential effects on the moisture gradients.

profile. In the diagram that we have been discussing, you will notice that the field capacity is shown as being highest in the top foot. This is a reflection of the higher content of organic matter in the top soil. All kinds of variations are possible. If the top soil were a coarse sand, poor in humus, and the subsoil a clay, we should find the field capacity increasing from the sand to the clay. A layer of sand in the subsoil would be reflected in a corresponding fall in field capacity. In the diagram, I have represented the possible effect of a sandy layer by the " dent " at D.

I have already mentioned permeability as one of the factors affecting the water conditions in soils. You will readily understand that it is governed by the size of the interstitial spaces in the soil. For example, if we had two flower pots, one filled with coarse gritty sand, and the other with very fine sand, we should find that water could percolate through the coarse material much more rapidly than through the fine material, even although the pore-space might be the same in each. In actual soils, much will depend on the structure. In a clay soil, if it is in the single-grain structure, *i.e.*, if it is not aggregated into crumbs, the spaces between the particles will be so fine that percolation will be exceedingly slow. Puddled clay, used for making ponds watertight, is in this state. On the other hand, if it has a crumb structure, there will be between the crumbs large spaces that can allow percolation. So you see how important it is with heavy soils

to maintain the crumb structure. Organic matter and lime are important in this respect. But I have written at some length about structure in an earlier letter.

We are now in a position to discuss how rain falling on the soil is disposed of. In the first place, a portion of it may be evaporated from the soil, or absorbed by the roots and transpired by the leaves of plants. This portion of the rainfall, sometimes called *fly-off*, is thus returned to the atmosphere, whence it came. Secondly, a portion of it may run off the surface and find its way into the local river system. This portion may be termed *run-off*. Run-off only occurs when rain falls with such intensity that it cannot be absorbed into the soil, a circumstance not usual under our conditions, but only too common in the United States and in the tropics. Thirdly, moisture that is not lost as fly-off and run-off, soaks into the soil and eventually finds its way to the water-table. Generally speaking, this portion, the so-called *cut-off*, eventually comes to the surface as springs at lower levels, and feeds the local river system. In certain circumstances, some of the cut-off finds its way to deep artesian storage. We have thus the following equation :—

Rainfall = Fly-off + run-off + cut-off.

I need only qualify this simple statement by noting that run-off may partially or completely soak into the soil and contribute to fly-off and cut-off.

In the absence of run-off, the quantity of drain-

age furnished by an area of land is a measure of the balance between rainfall and fly-off. At Rothamsted, careful drainage measurements conducted for many years show that, under English conditions, about half the rainfall finds its way into the drainage. During the summer, owing to evaporation and the needs of growing crops, drainage is reduced almost to nil. Indeed, in a hot, dry summer, evaporation and transpiration may outweigh rainfall. During the winter months, fly-off is at a minimum, and most of the rainfall goes into the drainage.

It is of interest to consider the rainfall-drainage balance under different climatic conditions. Consider a very humid climate, with over 100 inches of rain, such as in parts of Wales. If somewhere about 15 inches represents the amount of fly-off under English conditions, it is unlikely to be greater, and is probably rather less, under Welsh conditions. But even if it is the same, you will see that instead of about half the rainfall going to the drainage, about 85% will drain through the soil with a 100-inch rainfall.

Now consider the case of a hot, dry climate. Here the fly-off will be considerably greater than under English conditions. Obviously, the soil cannot evaporate more rainfall than it receives, but what will happen will be that the rain will only moisten the soil to a limited depth and that, after rain ceases, the soil will dry out again. The conditions throughout the year will be like those obtaining in summer drought in England, and no drainage will be furnished.

It now remains to consider the water relationships of soils from the standpoint of water supply to plants. Briefly, plants want as much water as they can get, provided the soil is not so saturated with water that the air supply is deficient. Let us imagine a fairly wet soil, but not so wet as to be deficient in aeration. Plants will be able to absorb water quite easily, as easily as if their roots were immersed in a water culture. If the soil gradually becomes drier, a stage is reached when it is more difficult for the plant to abstract water. We can regard it as a sort of competition between the roots and the soil for the water present. The drier the soil becomes, the stronger is the pull of the soil, really the pull of the soil colloidal matter, on the moisture present, until finally the plant roots cannot get moisture quickly enough to make good losses by transpiration from their leaves. At this stage, growth comes to a standstill, and the leaves, unless they belong to plants specially adapted to drought, become limp and lose their natural turgor. The point at which this loss of turgor becomes permanent is called the *wilting point,* and varies for different soils. A soil that contains comparatively little clay and humus can supply moisture to plants down to a lower moisture content than a soil with much organic matter and clay. For example, a light, sandy soil may have 5% of moisture at the wilting point of plants. This means that any moisture in excess of 5% is available for plants. On the other hand, a heavy soil, rich in organic matter, may

still contain 15% of moisture at the wilting point, so that only moisture in excess of 15% is available. But we must remember that the water capacity of the second soil will be much greater than that of the first.

The really important factors in the supply of water to plants are: first of all, of course, the amount and distribution of the rainfall; secondly, the water capacity of the soil; and thirdly, the depth of root development of the plants. If, owing to the presence of raw subsoil, or rock, or a high water-table, root development is confined to the top few inches, then if drought occurs, the available moisture within the shallow root range will soon be exhausted. On the other hand, where the soil profile is deep and permeable, roots can develop to great depths, and during periods of drought can draw on all the moisture stored within their range. In some of the older text-books, great importance was attached to the capillary rise of water from below. It was thought that moisture could be passed up from a deep water-table in the same way that oil rises in a lamp-wick. It appears from recent work, however, that this effect can only operate over a few feet and is, therefore, confined only to those cases where a water-table is within six feet or so of the surface. Where there is such a water-table, plant roots can go down sufficiently near to the water-table to draw on it for their moisture. There is an excellent example of this in a district in Anglesey. The soil is an exceedingly coarse

sand of low moisture capacity. There is, however, a water-table at about three feet below the surface, capable of supplying moisture even during periods of drought. If this water-table were a few feet deeper, capillary rise would probably be ineffective and the growth of crops on such a coarse material would be impossible. For certain types of cultivation, a controlled water-table in a sandy soil is very desirable. For example, in the culture of hyacinths, the best conditions for success appear to be a coarse, sandy soil, with a water-table maintained at about 60cm. below the surface.

We in Wales suffer more often from excess than from deficiency of moisture. Excess of moisture is harmful, not so much in itself as by reason of the deficient soil aeration that it implies. In arable soils there is also, of course, a direct disadvantage in excess moisture in that it increases the difficulties of cultivation. But even in Wales, moisture deficiency may limit plant growth. In many of our upland pastures, the character of the soil profile and the general wetness both contribute to produce shallow root systems. And this means that when a drought does occur, the effects are quickly felt, so that only those grasses which are adapted to drought can survive.

As a rule we are more concerned with wetness, and we may now consider this problem. The standard remedy for soil wetness is drainage, which consists essentially in providing either open ditches or underground channels whereby the

water-table can be lowered. It is important to realize that, even by lowering the water-table, you cannot reduce the moisture content of the soil below that of its field capacity. There is thus a limit to the amount of moisture removable by drainage. When the soil has been dried down to its field capacity by drainage, it may still be too wet for cultivation, or even too wet for satisfactory aeration; further removal can only take place by actual drying out or by the transpiration of moisture by plants.

Another point should be noticed in connexion with artificial drainage. In heavy clay soils, there is often very little percolation below the top foot or so, except where the original profile has been disturbed by the laying of a line of pipes, or by the passage of a mole plough in mole draining. Here the increased permeability may persist for many years, and excess moisture is removed by percolation along the surface of the undisturbed impervious layer, and then down into the drainage pipes or mole channels.

There remains the drying effect of vegetation itself. This may be very considerable. In irrigated areas in New South Wales, it has been found that crops such as lucerne can lower the water-table considerably below that of bare soil, even although they receive considerably more water in irrigation. The improvement of poor pasture may help in drying out wet soils. If you can by manuring or by alteration of the herbage increase the rate of production of dry matter per

acre, you must thereby take so much more water from the soil. An increase of one ton per acre in dry-matter production might mean that several hundred tons more water would be removed by transpiration. Conversely, a change in the other direction might lead to the soil becoming wetter. It has been found that one of the first effects of deforestation, particularly if the ground vegetation is scanty, is increased wetness, which may even lead to swamp conditions.

One point remains to be noticed, namely, the effect of soil moisture conditions on river flow. Under virgin conditions, the spongy character of the soil and the presence of swampy grounds in hollows contribute to give the land an enormous storage capacity, so that the effects of heavy rain and drought tend to be equalized or smoothed out. When land is brought under arable cultivation, and particularly if the natural structure of the soil is destroyed, rain tends to find its way into rivers more quickly, so that heavy rainfall is followed at once by flooding. The more damaged is the natural structure the more rapidly will rainfall reach the rivers. On the other hand, the establishment of good grassland tends to increase water storage in the soil, and may help to diminish flooding—a strong point in favour of a nation-wide grassland policy.

Ever yours,

G. W. R.

LETTER IX

SOIL FERTILITY

MY DEAR STAPLEDON,

In the Parable of the Sower, we are told of the seed that "fell into good ground and brought forth fruit, some an hundredfold, some sixtyfold, and some thirtyfold."* It is just this ability to give a generous return for expenditure in labour, in seed, and in manure, that constitutes the mark of a fertile soil. The stony ground may have as much labour, seed, and manure expended on it, but by reason of its inherent defects it does not yield a return. We will try to examine some of the principal causes of fertility and infertility in soils.

When we study the growth of plants we find that quite a number of factors are involved, and it will be convenient if we set these out at length. For the growth of plants, we must have :—

(1) LIGHT.—The building up of plant material is a process requiring an external source of energy, and this is obtained from sunlight. The assimilation of carbon dioxide by the leaves of green plants ceases as soon as light is cut off.

*St. Matthew xiii, 8.

(2) CARBON DIOXIDE. — The compounds of which plants are composed, starches, sugars, fibres, fats and proteins, are all compounds of carbon, and this carbon is obtained from the carbon dioxide present in the atmosphere. Under the influence of sunlight, the green colouring matter of plants is able to effect the remarkable synthesis, whereby carbon dioxide and water yield starch* and oxygen.

(3) TEMPERATURE.—Plant growth is strongly affected by temperature. Most of our agricultural crops, including grass, make very little growth below about 42°F. The rate of growth increases as temperature rises, and reaches a maximum at a temperature, called the optimum temperature, that varies with the crop. Thus, whilst crops such as barley and oats may have 60 to 65°F. as optimum temperatures, tropical crops such as sugar cane and pineapple may make their best growth at 75 or 80°F.

(4) MOISTURE.—Not only does plant material contain considerable proportions of water, but water is absorbed in large amounts by the roots and transpired by the leaves. For every part of dry matter made, from 200 to 1,000 parts of water are required.

(5) OXYGEN.—Plant roots require oxygen for their respiration. If air is excluded from the soil by waterlogging, plant roots cannot live. The

*The first verifiable product of carbon dioxide assimilation in the leaf. The starch thus formed is subsequently changed into sugar, which is translocated in the plant and used in the synthesis of other substances.

development of roots in a soil is confined to those layers that are aerated.

(6) PLANT NUTRIENTS.—By this we mean the elements absorbed by the roots of plants. It was formerly thought that the essential plant nutrient elements were nitrogen, phosphorus, sulphur, calcium, magnesium, potassium, and iron. Recent work has extended this list, and we may now add boron, manganese, copper, iodine, zinc, and cobalt. Other elements will doubtless be found to be essential. The recent additions to the list of essential elements are required in very small quantities, and they are sometimes referred to as the *trace elements*.

(7) ABSENCE OF INJURIOUS SUBSTANCES.—This is a kind of negative factor, but there are many instances of plant growth being depressed by harmful constituents in the soil. Among such harmful constituents we may mention acids, sodium salts, compounds of metals, such as lead, zinc, copper, or nickel, if present in sufficient amount.

(8) ABSENCE OF EXCESSIVE COMPETITION.—The agricultural crop may be depressed by excessive competition by weeds. We remember how, in the Parable of the Sower, some seed fell among thorns.

(9) ROOT HOLD.—The soil must have sufficient stability for plants to root in it. Blowing sand dunes cannot support plant growth.

(10) Finally, there are the unknown or little understood factors in plant growth. It seems

likely that there may be certain substances that have a specific effect in promoting plant growth. Indeed, recent work has shown that certain compounds present in the urine of animals stimulate germination and root development.

We can see now how complicated is the problem of soil fertility. We have ten factors or groups of factors, all of which must operate satisfactorily in order to obtain satisfactory plant growth. If nine of the factors are satisfactory, whilst the tenth is unsatisfactory, then this tenth factor becomes the limiting factor. We may use the crude analogy of the chain, whose strength is that of its weakest link. If any factor, for example, water supply, is the limiting factor, that factor must be adjusted in order that production may be increased. But we must not push the analogy of the chain too far. If the analogy were strict, then we could only increase production by attention to the limiting factor, whereas in practice, it may happen that any one of a number of factors may be modified with favourable results to productivity. For example, deficient water supply may be the main factor, limiting production in a certain soil. Yet it may happen that some increase in production might be effected by nitrogenous or phosphatic manuring. It would still be true to say, however, that no considerable increase could be obtained until the deficiency in water supply had been remedied.

I have spoken of ten factors governing plant growth. Actually it is not even as simple as

that, for many of these factors might be better described as groups of factors or composite factors. Under plant food we understand the supply of a dozen or more elements. Not only may the supply of any one of these elements be a limiting factor, but there are all kinds of complex inter-relationships, whereby excessive supply of one element may affect the absorption of another element. Further, we have to consider that an element, such as copper, that is necessary in traces for plant growth, may become an injurious factor if supplied in too great quantity.

Whilst the cultivator can modify certain factors in a direction favourable to plant growth, other factors are outside his control, or can only be controlled to a limited extent. Thus light and carbon dioxide are, practically speaking, uncontrollable. Water supply is governed mainly by rainfall. But even given the rainfall, the intrinsic characters of the soil also impose certain limits. Even in a country with such favourable moisture conditions as our own, thin, rocky soils or light, gravelly soils must inevitably be liable to drought. In other soils, conditions may fluctuate between excessive moisture, with accompanying deficiency of aeration, and deficient moisture consequent on the shallowness of the rooting system induced by the conditions obtaining during the wet periods.

It is in the plant-nutrient group of factors that the farmer can most successfully intervene, for he can readily supplement deficiencies in the

soil by the use of manures and fertilizers. Unfortunately it is not easy to determine what are these needs or the order of their urgency. Neither is it easy to determine the most profitable amounts to apply. I shall discuss the problem of manures and fertilizers in another letter.

I will merely add that the fact that serious plant nutrient deficiencies are not more widespread and are generally confined to two or three elements may be due in a large measure to the adaptation of plants to their soil environment. It is fortunate, but surely not fortuitous, that those elements that commonly occur only in "trace" amounts in soils are required, if at all, only in "trace" amounts by plants.

Fertility must always be considered in relation to the crops grown. The adaptation of certain crops to certain soils has long been known.

> "*Hic segetes, illic veniunt felicius uvæ,*
> *arborei fetus alibi, atque iniussa virescunt*
> *gramina.*"*
>
> "*Here corn, there vines come more abundantly, yonder fruit trees or green pasture.*"

A soil that is well adapted for wheat or beans may grow poor crops of potatoes or carrots. Although it is known in a general way that certain crops such as potatoes, carrots, barley, and rye succeed on light soils, whilst beans and wheat prefer heavier soils, it does not appear possible to specify the "optimum" soil for each crop. The establishment of such correlations would need

*Virgil, Georgics, I, 54-46.

an enormous mass of investigation, and, when all is said, climatic conditions play an equally important part with soil in crop adaptation. If we knew everything, we should probably find that most crops can grow successfully in a fairly wide range of soil and climatic conditions.

If I were asked to say what factor is most evident in controlling fertility, I should say soil moisture, with which is bound up the factor of air supply, since excess of moisture means deficiency of aeration and *vice versa*. In a settled country, a soil that by reason of its profile characters can so use the rainfall as to maintain an optimum supply of moisture for the use of crops will generally be found by experience to repay skilful cultivation and manuring, and will have been enriched in plant food by generations of high farming. On the other hand, soils that suffer from excess or deficiency of moisture will have been found less responsive to generous treatment, and will probably be found in the occupation of less skilful cultivators. Further, it may be said that practically all our waste lands suffer from excess of moisture, deficiency of moisture, or an alternation between these conditions. Such lands do not repay generous treatment and have never received it. They, therefore, have a generally low plant nutrient status.

I have presented soil fertility as a complicated and multi-dimensional problem, for such it is, even if we take account only of the known factors in plant growth. Soil fertility is not a matter

simply of abundant supplies of nitrogen, phosphorus, and potassium. Neither can infertility be cured simply by loading farmyard manure and artificial fertilizers into the soil. Soil fertility consists rather in the favourable operation of a number of factors, some of which are known and understood, whilst others are little understood, and yet others unknown. The great achievements of the past century have greatly increased the power of Man over Nature. Can we look forward to such a mastery of the problems of the soil and the growth of plants that future crop yields will make our present yields appear as insignificant as those of manorial times appear to us? Personally, I believe that a close study of all the factors affecting crop growth, and in particular, the water conditions in soils, would make possible very considerable increases in crop yields, although it is doubtful if, under ordinary soil conditions, the enormous growth could be obtained that has been obtained in California in water cultures with artificial heating. But we should still find great differences in productivity conditioned by inherent soil characters. Our thin upland soils and our coarse sandy soils would still suffer from periodic droughts, and our low-lying, heavy clays from excessive wetness.

In all problems of increasing fertility, the cost of improvements has to be considered in relation to probable returns. I am sure you have encountered this difficulty repeatedly in your work on the improvement of hill pastures. Even if you

can get an increase in production from expenditure of any kind—manuring, drainage, or cultivation—a point comes at which further expenditure brings a smaller return. The classical example of this Law of Diminishing Returns, so far as it applies to the manuring of land for crop production, is supplied by that mine of information, the Broadbalk Wheat Field at Rothamsted. The data are rather ancient—they relate to the 13 years, 1852-1864, but they still serve to illustrate the point. Here, then, are the average yields of wheat for five plots, one with minerals only and the others with increasing applications of ammonium salts:—

	Bushels per acre	Increase per additional 43 lb. N
Minerals alone	18·3	—
Minerals and 43 lbs. nitrogen as ammonium salts	28·6	10·3
Minerals and 86 lbs. nitrogen as ammonium salts	37·1	8·5
Minerals and 129 lbs. nitrogen as ammonium salts	39·0	1·9
Minerals and 172 lbs. nitrogen as ammonium salts	39·5	0·5

Now if we assume that the basal expenditure on all the plots is the same, we may regard the increase in every case as due to the ammonium

salts added, and we see that, whilst the first dose of nitrogen gives an increase of 10·3 bushels, the second gives 8·3 bushels, the third 1·9 bushels, and the fourth only 0·5 bushels. Note that there is an appreciable yield even without the added nitrogen, because there is already some nitrogen in the soil. If we could imagine a soil devoid of nitrogen, the Law of Diminishing Returns would probably not come into play for the first additions of nitrogen. Indeed we might find that a certain amount of nitrogen might be needed before any return at all would be obtained. Thereafter, yields might be roughly proportional to nitrogen added, but eventually a point would be reached when, as in the example quoted, each successive addition would give a smaller return.

These principles hold for all types of effort expended to obtain production, whether it be cultivation, drainage, or manuring. A point is reached when further expenditure becomes less profitable. The amount of expenditure that is most profitable depends on the value of the produce. Returning to our Broadbalk example, at low prices for wheat it might not pay to apply more than one dose of nitrogen; with higher prices it might be profitable to give a double or even a treble dose. This suggests that, as a general principle, there is an optimum expenditure of effort, depending on the relation of the cost of the effort to the value of the product obtained.

There remains the elusive problem of quality.

At the outset, there is the difficulty of defining it in terms that admit of its correlation with conditions of growth. In the realm of quantitative returns, tons or bushels per acre can be correlated with soil, manurial, or climatic data. But how can the merit of a fine Burgundy, or a noble port, be expressed by a number? I have before me a tabular statement* showing the wines of different regions and different years, arranged in seven degrees of merit. I see, for example, that in 1924, 1928, 1929, and 1934, clarets obtain the full seven marks assigned to "the best." Would it be safe to assume the clarets of these years to be identical, and to attempt to define the ideal weather during a vintage year? Or, if in a particular year, the wines of the Gironde were given marks, could one discover the ideal soil by studying the conditions in which those with full marks were produced? Personally, I think not, because of the complexity of the conception of quality. If it is difficult to correlate a single effect, yield, with the complex of factors involved in plant growth, how much more difficult, if not impossible, is the task of correlating quality, which is the integration of an indefinite number of attibutes, most of which are not susceptible of objective estimate?

I am not entirely displeased to think that modern science, although it may effect some levelling up, is likely to have little influence on quality in its higher manifestations. The pro-

*Published by the Wine and Food Society.

duction of masterpieces will always be the work of artists, who know nothing of the Law of Diminishing Returns, and to whom you and I, as agricultural scientists, will have little to communicate. I may be able to give useful information on the growth of grass or oats, but I should tremble to offer advice at Chateau Latour.

Ever yours,

G. W. R.

Letter X

MANURES AND FERTILIZERS

My dear Stapledon,

I shall have several occasions during these letters to contrast virgin and cultivated soils, and in this letter I want to begin by examining this contrast from the standpoint of plant nutrition. We will begin by reminding ourselves that plants obtain their carbon dioxide by their leaves under the influence of the sunlight, and their hydrogen and oxygen from water absorbed by their roots. Dissolved in the water absorbed by their roots are the so-called plant-food elements. When you and I were students, we learnt that the essential plant-food elements were nitrogen, phosphorus, sulphur, potassium, magnesium, calcium, and iron. We know now that manganese, boron, iodine, copper, and zinc should certainly be added to the list of essential elements and, with further research, the list will certainly be extended. The reason that these additional elements were overlooked at first is that they are only required in very small quantities, and that in the earlier experiments they were probably present as impurities in the reagents used.

Having agreed on these preliminaries, let us examine the case of a virgin soil with its appropriate vegetation. Each year there is abstracted from the soil by the roots of the plants growing on it so much of each of the plant food elements. Practically the whole of the plant food thus taken from the soil is returned at the end of the season's growth in the form of leaf-fall or other plant remains. There is thus a closed cycle of plant nutrients between vegetation and soil, and a kind of equilibrium in plant nutrient status is reached in which losses by drainage and other causes are balanced by gains through weathering of the parent material and, in the case of nitrogen, fixation from the atmosphere.

When the virgin soil is brought into cultivation, the supply of available plant nutrients in the soil and in the residues of the natural vegetation incorporated with the soil may be sufficiently high at first to give good or even excellent crops. The course of events will then be determined by the system under which the soil is exploited.

If the soil is cropped continuously, there is a continuous drain of plant nutrients from the soil without replacement, apart from weathering and nitrogen fixation. Crop yields gradually fall off until returns no longer pay for the outlay involved in cultivation and seeding. It is interesting to cite, in this connexion, the case of the plot on the famous Broadbalk field at Rothamsted, which has grown wheat continuously for nearly a cen-

tury without manure. The yield has fallen off to something over 10 bushels per acre, but it seems likely that this low yield might be obtained indefinitely. At this level of production, the losses in plant nutrients due to crop removed are about balanced by weathering and nitrogen fixation. It should be noted that the soil is not equally exhausted in the plant nutrient elements: nitrogen deficiency is generally the first to declare itself, followed by phosphorus, and potash. In the case of some of the other elements, deficiency is longer delayed and, since yields fall off, decreasing amounts are taken from the soil.

The system of land utilization exemplified by the unmanured wheat plot at Rothamsted may be termed *exhaustive.* In certain kinds of primitive agriculture, it is practised until yields fall to a point at which they cease to repay labour and seed. The land is then abandoned, and goes back to wild vegetation, thereby gaining the opportunity of building up afresh its content of plant nutrients.

When exhaustive cultivation is replaced by rotational cropping with the keeping of livestock, it is possible to maintain production at a higher level, for a considerable proportion of the produce of the soil is fed to stock. The excreta from the stock are returned to the soil, either directly or as farmyard manure, thereby returning some of the plant nutrients abstracted by crops. Another advantage in the keeping of stock is that the organic matter status of the

soil, and hence its structure, is better maintained. Such a system may be termed *conservative*.

As I said above, nitrogen is the nutrient element that generally first shows deficiency and thereby leads to a reduction in productivity. The use of rotations, including leguminous crops, which enrich the soil in nitrogen through the action of their associated bacteria, makes possible the maintenance of a relatively high nitrogen status. A rotation such as wheat, roots, barley, and clover, in which the roots, clover, and part of the barley are fed to stock, thereby producing farmyard manure, would probably, so far as nitrogen status is concerned, suffice to maintain yields at least up to the average for the country, but the continued drain on soil phosphorus by crops and stock sold would eventually lead to lowering of productivity. This loss might be made good by a dressing of a phosphatic fertilizer, such as superphosphate, once in the rotation, preferably for the root crop. On soil naturally poor in potash reserves, it might be necessary to maintain potash status by periodic dressings of potash fertilizers. On other soils, the weathering of potash minerals in the soil might produce a sufficient supply of available potash for the maintenance of normal yields. In actual practice, the elements supplied in manures and fertilizers are nitrogen, phosphorus, and potassium.

From what has been said it appears that with good farming, the keeping of livestock, and the use of leguminous crops in leys, particularly

where, as in Wales, leys are down for half a dozen or more years, a fair level of productivity may be obtained by a limited use of fertilizers. This is true so far as nitrogen, phosphorus, and potash are concerned, but the statement must be amplified in respect of lime, a topic which I must deal with in the next letter. We must also make a qualification with regard to some of the other plant nutrient elements. Even if only a dozen elements are necessary for plant growth (and we know there are more), it may happen that some of these, originally present in small amounts, but sufficient for the use of a natural vegetation, may become exhausted by long-continued cropping. The exhaustion of the soil in some of these minor elements in plant nutrition may occasionally be a cause of infertility. For example, it has been found that in certain soils reclaimed from peat, small traces of copper are necessary for crop growth. Normally one would not think of adding copper salts as fertilizers, because most soils contain sufficient of this element to supply the small traces needed. Deficiency in necessary elements may show itself through certain "deficiency diseases" in grazing stock. A good example of this is the "Morton Mains disease" of grazing animals in a district in the south island of New Zealand. On investigation it was shown to be due to a deficiency in cobalt.

This is a convenient point to interpose a short account, in some sense a panegyric, of farmyard manure. It is the oldest of manures,

and modern science has not succeeded in rendering it obsolete. The value of farmyard manure was recognized in the days of Cato and Varro; it is no less esteemed in these days of mechanization and synthetic fertilizers. By means of it the farmer is able to approach the equilibrium of natural conditions and return to the soil, in some measure, the nutrient elements that have been removed by crops. Farmyard manure can make the difference between exhaustive and conservative use of the soil.

The value of farmyard manure is not to be judged simply by its contribution of nitrogen, phosphorus, potassium, and the other plant nutrient elements. Of equal value is its use in maintaining the organic matter status and, hence, the structure of the soil. Linked with its effect on the organic matter of the soil is its action in promoting general biological activity. Finally, if we accept the view that there are growth-promoting substances in animal excreta, apart from ordinary plant nutrients, such substances reach the soil chiefly through farmyard manure.

I have entitled this letter "Manures and Fertilizers," possibly because these words appear in degree syllabuses of agricultural chemistry. I should, perhaps, have included some discussion of "manures" such as guano, fish meal, and meat meal. But this is not a text book, and I will content myself with discussing only the good old manure—good, honest "muck".

We have looked at the manurial problem so

far from the standpoint of maintaining the balance between ingoings and outgoings of plant food. But there is also another aspect to be noted, namely the needs of particular crops. It appears that certain crops require special fertilization in order to give satisfactory yields. Thus, swedes, mangels, potatoes, and sugar beet all appear to require a high plant nutrient status. If we attempted to grow any of these crops continuously without manure, the yields would fall off to zero. Certain crops appear to require high proportions of certain elements. Thus, swedes and certain leguminous crops are responsive to phosphate, whilst most fruit trees, mangels, beet, and potatoes generally require potash fertilizers. I shall not give you recipes for manuring, since the best practice in this respect will vary with soil and cropping.

Akin to this subject is the specific effect of certain nutrient elements. Nitrogenous fertilizers promote the growth of leaf and stem and are, therefore, particularly valuable where these constitute the actual crop harvested. Excess of nitrogen causes over-production of leaf and stem at the expense of grain and seed. It also delays ripening and increases liability to disease. Phosphatic manuring promotes the development of grain and seed. It also favours root development and indirectly helps plants to resist drought by deepening their root system. For example, in Australia, phosphatic fertilizers are indispensable for the growth of wheat. Phosphates also pro-

mote early ripening, and may balance the delaying effect of excess nitrogen in this respect. Potash fertilizers appear to increase resistance to disease, and to improve the quality of crops.

There is a further aspect of the use of manures and fertilizers, namely the production of quality in produce. This is particularly important for fruit, tobacco, potatoes, and garden vegetables. Actually, we know very little about this side of the question. For one thing it is not always easy to decide what is meant by quality. We know that certain localities are noted for the high quality of their produce. Is this a matter of climate, or of soil moisture, or is it a balanced supply of plant nutrients? We do not know, but I feel that we shall always have the distinction between "Falernian" and "humble Sabine." I have already referred to this subject in the preceding letter.

Whilst manurial needs under conservative systems of agriculture, such as those immediately succeeding exhaustive systems, may be small, when higher levels of production are reached more lavish use of fertilizer dressings is required. This is not simply because the increased crops remove a large amount of plant food from the soil, but because, when the plant nutrient status of the soil is maintained at a higher level, wastage through drainage and, in the case of nitrogen, denitrification, is higher. This wastage reaches its maximum in certain intensive forms of market gardening where enormous quantities of fertilizers and manures are used.

Returning to the case of virgin soils brought into cultivation, we find that soils of the prairie and steppe developed under semi-arid climates stand up better to exhaustive cultivation than forest soils developed under humid climates. This is readily intelligible when we realize that the wetter the climate the more is the soil leached by the rainfall. And among forest soils we may distinguish those under deciduous from those under coniferous forest. The former have a distinctly higher nutrient status in mineral elements, particularly lime. Soil brought into cultivation from coniferous forest would need initial dressings of lime and, probably, phosphate in order to produce satisfactory crops. The same applies to most of our waste lands in Britain now under heath or grass heath. But more of this when we discuss wastes.

I have said that the problem of the use of manures and fertilizers is two-fold, namely the maintenance of balance between ingoings and outgoings and the needs of particular crops. Even if our only aim is the preservation of plant nutrient status the problem is not simple, and I will try to indicate some of its intricacies.

It might seem an easy matter to determine the number of pounds per acre of nitrogen, phosphorus, potash, lime, and so forth removed annually by crops and to replace these amounts in the form of manures and fertilizers, allowing for the amounts returned by animals and farmyard manure. But we have on the one side the

additional losses by drainage and denitrification and on the other side the gain by fixation and the weathering of raw mineral material from the soil. There is also an additional complication, for in some cases, plant food added as fertilizers may be changed in the soil to forms that are unavailable to plants. The principal example is that of soil phosphorus. Phosphates are scarcely lost from the soil in drainage waters. Yet in order to maintain phosphate status it is generally necessary to supply phosphorus in the form of phosphatic fertilizers at a greater rate than phosphorus is removed by crops and stock. There appears, therefore, to be a kind of locking-up of phosphorus in the soil. It would be of interest to know whether, if the soil were, so to speak, sufficiently saturated with phosphate, one might reach a point where the phosphate status could be maintained simply by replacing the phosphorus removed. It seems evident that in ordinary soils we are far removed from such a state of phosphorus saturation.

I have already referred to the problem of the minor elements not usually supplied in manures and fertilizers. In soils that have been long under cultivation, it certainly appears that some of these minor elements may become exhausted, and one of the problems for the future will be the discovery of methods for detecting such deficiencies. In view of the lengthening list of elements essential for plant growth, the problem does not appear to admit of an easy solution.

In actual practice, manures and fertilizers are generally given with a view to the needs of particular crops. For most systems of husbandry, systems of manuring have been arrived at partly by experiment and partly by opinion. For example, in our typical Welsh husbandry, where a three-year arable break consisting of oats, roots, and oats, is followed by six years or more under grass, the best practice is to apply most of the manuring to the root crop, which receives farmyard manure together with artificial fertilizers adapted to the needs of the particular crop (swedes, mangels, or potatoes). A dressing of phosphatic fertilizer (basic slag) may also be given after the land has been two or three years down in grass. When, as under recent conditions the arable break is lengthened additional fertilization is needed, *e.g.*, for a second corn crop.

Rules for the use of manures and fertilizers are generally of a somewhat empirical character. It is true that we have an enormous body of information from the very numerous manurial trials which have been carried out in different parts of the country, but it is difficult to crystallize this information into precise principles, for several reasons, which we may examine. There is, of course, the great variety of crops for which manures and fertilizers are required. But let us suppose the problem is simply that of discovering the best manurial treatment for one crop, say, potatoes. First of all there is the question of how much farmyard manure shall be used—from nothing up

to perhaps thirty tons per acre. Then there is the problem of what artificials shall be given in addition. For phosphate, we have ordinarily the choice of superphosphate or basic slag; for potash we have (or had formerly) the choice of sulphate of potash, chloride of potash, 30% potash salts, or kainit; for nitrogen we have the choice of sulphate of ammonia, nitrate of soda, or possibly also nitrate of lime. Now, in addition to all the permutations and combinations of these fertilizers, we have also to consider possible variations in the rates of dressing. It is easy to see that the problem is multi-dimensional and exceedingly complicated. But even if, by use of modern statistical methods of experimentation, we have established that, say, 15 tons of farmyard manure, 4 tons of superphosphate, 2 cwt. of sulphate of potash, and 2 cwt. of sulphate of ammonia give the best results, and these can only be judged in relation to costs and returns, the information is valid only for the particular soil and climate and for the particular conditions of rotation and culture.

What I am trying to explain is that it seems almost hopeless to expect to get rules for the use of manures and fertilizers which will enable us to prescribe exactly what is the best treatment for each case. The most we can hope to obtain are rough and approximate manurial prescriptions. Whatever policy he adopted, it is always important to ensure that outgoing in crops sold off the farm should be balanced, due regard, of course, being paid to the fact that considerable

amounts of nitrogen are to be had by the growth of leguminous crops with their associated nitrogen-fixers. The principal problem is therefore the adequate supply of phosphate and potash.

Phosphorus occupies rather a special position and has been termed the key to permanent agriculture. There is some justification for this, since nitrogen is obtained from the atmosphere and potash is often present, in sufficient quantity for moderate production, in the soil itself. The reserves of phosphorus are much more limited. Large areas of the soils of the world are naturally deficient in phosphate. Indeed, if the phosphorus status of our own soils is satisfactory, it is in a large measure due to the enormous amounts that have been applied in the form of bones, superphosphate, basic slag, and, in recent years, mineral phosphates. It may be that in future years the threat of exhaustion of natural phosphate deposits and a diminution in the supply of phosphatic slags from steel manufacture will force on us the necessity for considering very carefully the conservation of soil phosphorus and its more economical use.

I regret that I have to report such a deficiency in our knowledge respecting the use of manures and fertilizers, but I hope I have impressed on you how many variables there are in the problem and that you will understand why, in giving advice to farmers on these matters, one hesitates to dogmatize and is quite content if the advice given is at least safe. And I feel that, with the object

lessons before us of the perils of heedless exploitation of the land, "Safety First" is no bad principle.

Ever yours,
G. W. R.

P.S.—A vigorous propaganda has recently been directed against artificial fertilizers. It is asserted with almost mystical fervour that they affect adversely both soils and crops, and that foods produced by their aid are injurious to animal and human health. Such ideas make a natural appeal to the credulous, but actually the evidence adduced will not bear examination. So far as agriculture is concerned, the controversy is beside the point, for an intelligent use of artificial fertilizers means more food for stock, more farmyard manure, and, what is more important, better leys. Artificial fertilizers thus make possible more humus in the soil.

LETTER XI

LIME

MY DEAR STAPLEDON,

When I write to you about the importance of lime in agriculture I know I am preaching to the converted; but it is a good thing to give reasons for the faith that is in us. We need millions of tons of lime* to put our British soils into a satisfactory condition, but we need a philosophy of liming just the same.

I think it will be well to begin with a little elementary chemistry. You may remember that, when I outlined the general constitution of the soil, I tried to distinguish between the relatively inactive skeleton or framework and the active clay-humus or colloidal complex. In discussing soil chemistry, we may practically disregard the framework of unweathered mineral fragments and fix our attention on the active clay-humus complex. This complex behaves like a weak acid capable of reacting with bases. Now, just as we can have:—

* Since the publication of the first edition we have had the Government's lime subsidy. Mainly because of this the annual use of lime dressings has increased from about 400,000 tons to over 4 million tons. There is still much leeway to make up, but we must all welcome this much of improvement.

$$CaCO_3 + 2HCl = CaCl_2 + H_2O + CO_2$$

[calcium carbonate+hydrochloric acid=calcium chloride+ water+carbon dioxide]

we can have :—

$$CaCO_3 + \text{soil acid} = \text{Ca-soil} + H_2O + CO_2$$

[calcium carbonate+soil acid=calcium soil+water+carbon dioxide]

Of course I can't give an exact equation in the second place, but what I mean is that calcium carbonate, or any other basic material, can neutralize the acid clay-humus giving a kind of calcium salt.

In most of our soils, this neutralization is far from complete and we may say that our soils are *base-unsaturated.* If neutralization is complete, we may say that the soil is *base-saturated.** On the other hand, if the complex acids are not even partially neutralized we say that the soil is *base-desaturated.*

Lime over and above that needed to saturate the soil acids appears as calcium carbonate. We may say, as a general rule, that if a soil contains free calcium carbonate, *i.e.*, if it fizzes on treatment with acid, it is saturated. This is not strictly true, because sometimes a soil may contain occa-

*There is some difference of opinion among soil chemists as to what is exactly meant by base-saturation; but I take it to mean the degree of base-saturation found in a soil that has contained free calcium carbonate for a sufficiently long time for equilibrium to have been reached. This is a convenient definition, because any lime uncombined with the clay-humus appears in the soil as calcium carbonate, and also because there are many kinds of soil in which calcium carbonate is naturally present, as, for example, the chalk soils. Such soils must be considered base-saturated.

sional coarse fragments of hard limestone and yet be unsaturated.

Lime combined with the clay-humus acids is called *exchangeable lime*. There are in soils small proportions of *exchangeable magnesia, potash,* and *soda.* To sum up, we can distinguish different stages in lime status as follows:—

(1) Base-desaturated. Containing no exchangeable lime or other bases.

(2) Base-unsaturated. Containing no free calcium carbonate but containing amounts of exchangeable lime ranging from almost complete desaturation to saturation.

(3) Base-saturated. Soil acids completely saturated with lime and excess lime present in the form of free carbonate of lime.

Most of the soils with which we have to deal fall in the second category.

Now for a few words about our old friend pH.* The pH scale is designed to give a measure of the acidity or alkalinity of a solution. On this scale, dead neutrality is 7·0. The alkaline side of neutrality is shown by pH figures above 7·0 and the acid side of neutrality by pH figures below 7·0.

When we speak of the pH of a soil we mean the pH of the soil solution. A completely desaturated soil will have a pH in the region of 4, although sometimes small quantities of sulphuric

*pH is the negative logarithm of the hydrogen-ion concentration. Thus, in a decinormal (0·1 N) solution of a strong acid, *e.g.* HCl, the hydrogen-ion concentration is 0·1g per litre and we say the pH is 1. The pH of a centinormal (0·01 N) solution of HCl is 2, of a millinormal (0·001 N) solution 3, and so on.

acid present may bring the pH down to 3 or less. A completely saturated soil will have a pH of 7·5 to 8·0 if free calcium carbonate is present. A half saturated soil might have a pH of about 6·0. If we make a graph showing the relationship between pH and the percentage of exchangeable lime present we get something like the picture

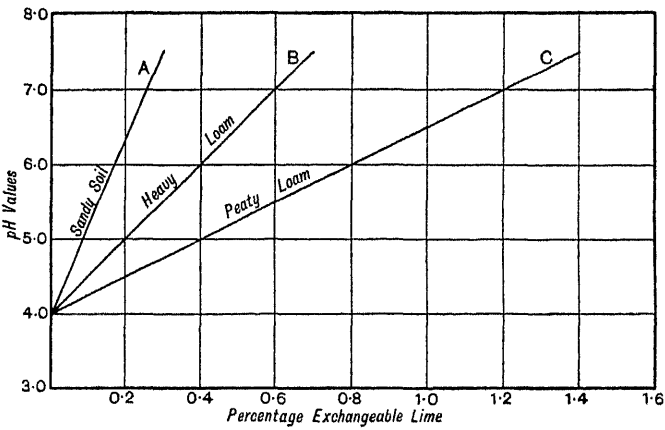


FIG. 6. Relationship between pH and exchangeable lime for different soils.

shown in *Fig*. 6. You will see that I have put in three lines. Line A shows how the pH of a sandy soil, poor in organic matter, might vary with the amount of exchangeable lime present. Line B shows the kind of relationship you would get for an average Welsh agricultural soil, whilst Line C gives the relationship for a peaty loam such as you have in some of your hill grazings.

The point to notice is that soils may be equally acid, *i.e.*, have the same pH, and yet contain differing amounts of exchangeable lime. The determination of the pH of a soil, although it tells us something about the intensity of the acidity, does not necessarily tell us how much exchangeable lime is actually present. Now, all the evidence that I have goes to show that it is the exchangeable lime that really matters and pH does not tell us much about that. However, if we are dealing with soils that we know fairly well, a knowledge of the pH may give us some help. For example, with ordinary Welsh soils, if I find the pH to be, say, 4·5, I am quite certain that the amount of exchangeable lime present is less than 0·15%, and moderately certain that it is less than 0·1%. On the other hand, if it is, say, 6·0, I am fairly certain that it has over 0·3% of exchangeable lime and quite certain that it has more than 0·2%. For sandy soils, poor in organic matter, or peaty soils, these standards would have to be adjusted.

In dealing with the problem of liming and soil acidity we need not worry about soils containing free calcium carbonate for the moment. Such soils may eventually come to need lime; but I will return to this point later. The soils which concern us here are those that we have called base-unsaturated, *i.e.*, soils in which the acidity of the clay-humus complex is more or less un-neutralized.

We know that when soils are very acid and therefore deficient in lime, their fertility is

depressed, and that they are improved in productivity by dressings of lime or calcium carbonate. What is the reason for their low productivity? Is it the acidity that is harmful or is it simply that they do not supply enough lime for the need of the plants? An extreme degree of acidity can doubtless be harmful in itself to plant growth and to what one might call the health of the soil, but there is reason to believe that, as a general rule, what is more important is the supply of lime available for the use of plants. Under the conditions with which I am most familiar, those of Wales, I would say that if a soil contains less than about 0·30% of exchangeable lime, or about 6,000 lbs. per acre of top soil, it is desirable to restore it to this level by liming. Possibly one should put the figure a little higher to be on the safe side. Certainly, for horticultural purposes one would aim at a distinctly higher lime-status, perhaps 0·5 or 0·6% exchangeable lime as minimum. Heavy clay soils also should probably be maintained at a higher lime-status than medium or light soils because of the favourable effect of lime on tillage properties. (See p. 52.)

If, as the result of a liming campaign, we could reach a nation-wide minimum of 6,000 lbs. exchangeable lime per acre, I am sure we should witness a remarkable increase in productivity, for there are vast areas, particularly in Wales, that do not reach even this moderate standard.

The application of lime or chalk to soil has been practised in this country from the earliest

times. I have examined soils in Wales that still contain up to 50 tons of lime per acre in the form of carbonate of lime over and above that needed for the saturation of the clay-humus acids. Such soils contain sufficient reserves of lime to last for centuries. There are also soils, such as many of those on the chalk, in which free calcium carbonate is naturally present.

Our ancestors had such zeal for liming that they probably dressed many soils which already contained a sufficiency. During the latter half of the nineteenth century, the practice of liming and chalking fell into disuse, although it survived in some districts and has been to some extent revived in connexion with the growing of sugar beet. In our own Wales the use of lime in agriculture had dwindled to very small dimensions. Happily there are signs that, with the advent of the Lime Subsidy assistance, liming has again come into its own. The present generation of farmers is under a great debt to its ancestors for their liberality and even prodigality in the use of lime, for, even when liming was no longer practised, the soil had generally sufficient accumulated reserves to carry on for many years.

Unfortunately, lime is continually being lost from the soil, mainly by washing out in drainage, but also in the crops and stock sold off the farm. The rate of loss varies considerably. Other things being equal, it is greater under wet than under dry climates, because of the more intense washing out or leaching. It depends also on the actual

lime-status of the soil. At Rothamsted, where the soil contains free calcium carbonate, the annual loss is of the order of 500 lbs. of lime per acre. In North Wales, from soils containing from 0·15 to 0·35% exchangeable lime, in spite of the greater amount of leaching, the annual loss is considerably less, from 100 to 200 lbs. to acre, the highest losses occurring from soils richest in lime.

Thus it is clear that, even although a given soil contains sufficient lime, it will sooner or later come to the point of deficiency. If we could imagine a map of the country with the lime-deficient fields shown in red, we should find, if no liming were practised, the red patches increasing in area from year to year as fields fall below the lime-status necessary for fertility. In districts where liming has fallen into disuse, this has been going on for years. When I came to Wales, thirty-four years ago, the red patches, apart from the wastes, might have occupied 10% of the area of agricultural lands. In 1937, they probably amounted to more like 50%. Since 1937, the liming campaign has certainly reduced the red areas, but much still remains to be done, particularly in the remoter areas, where transport charges make liming expensive, even with the Subsidy. The present liming campaign was certainly not premature.

If I were asked to give the main heads of a liming programme I should lay down the following three points:—

(1) All agricultural land of inadequate lime-

status should be given sufficient lime to ensure a minimum of, say, 0·25%, or, still better, 0·3% exchangeable lime, with higher figures for heavy or peaty soils.

(2) In order to make good the inevitable losses by drainage, initial dressings should be followed up by periodical dressings at such a rate as to ensure the return of 200-250 lbs. of lime per acre per annum.

(3) In the case of soils where lime-status is at present satisfactory, the certainty of future losses should be borne in mind. Thus a soil with 0·4% exchangeable lime may be expected to have about 0·3% in another ten years. It would then be necessary to forestall depletion by regular dressings at the rate mentioned in (2).

Throughout this letter, I have been referring to "liming," but you will understand that, in order to give lime to the soil, it is not necessary to apply it as quicklime (CaO). Much of the lime applied in past generations was applied as chalk ($CaCO_3$), as, for example, on the historic fields of Rothamsted. But the commonest practice has been to use quicklime. Lime in lump form from the kiln is allowed to slake, *i.e.*, to become hydrated ($CaO + H_2O = Ca(OH)_2$), when it falls to a fine powder, which can be spread over the land. There are many objections to this method of applying lime. The slaking must be done carefully. It involves the absorption of water; but, if the weather is wet, it is easy to get the slaked lime into a pasty condition, rendering it impossible to

be spread. Spreading has to be done from small heaps in the field and this, apart from its unpleasantness, is difficult to perform so as to secure even distribution. It is true that where liming by means of lump quicklime has been practised for generations, considerable skill is developed; but even in such cases, inspection of a recently limed field will show remarkable variation in the thickness of application.

The difficulty of distribution is less where ground lime is used. This can be spread by a manure distributor, but this again may be an unpleasant and even dangerous proceeding, owing to the blowing about of the highly caustic lime dust. There are also great dangers in the storage of ground lime in bags. Added to these disadvantages is its high price relative to lump lime. My own preference is strongly for ground limestone. When finely ground, this is as effective as lime and the only disadvantage is that nearly twice as much must be used to supply as much lime as an equal weight of quicklime. (56 parts $CaO = 100$ parts $CaCO_3$.) The advantages of ground limestone are that it is harmless to the clothing or persons of workmen; it does not need to be slaked; if wetted, it becomes powdery again on drying, and it can be stored in buildings without risk of heating and fire.

It is generally supposed that ground limestone, in order to be as effective as lime, should be very finely ground. A product with about 80% passing a 100-mesh sieve is often prescribed. But, from

recent work, it appears that a coarser product would serve the purpose. A ground limestone with 50% passing the 100-mesh sieve would contain sufficient fine material for immediate reaction, whilst the coarser fractions would react with the soil in subsequent years. Indeed, in the wetter regions, an even coarser product might prove adequate. Much depends on the price at which ground limestone is offered. Personally, I would always prefer the ground limestone, even if the price, based on the actual amount of CaO supplied, were slightly higher than that of quicklime on a strictly price basis.

Ever yours,

G. W. R.

Letter XII

SOIL SURVEYS

My dear Stapledon,

I am sure you would agree that it would be very desirable to have a map that would show all the different kinds of soil that occur, and their distribution over the face of the country. The need for such a map has long been felt. Until 1939 we had no national Soil Survey comparable with the Geological Survey. There was some justification for this delay, because even if the necessary financial support for a survey had been available, say, half a century ago, the technique of soil mapping was not developed. Even now, it cannot be said that methods are entirely satisfactory, but we do believe that enough is known of the essential characters of soils and their classification for maps to be made that will correspond with the relevant facts.

In these letters, I have repeatedly emphasized the importance of the soil profile as the soil individual and as our unit of study. This holds, whether we view the soil in its purely philosophical aspect or as a medium for the growth of crops. It is evident, therefore, that a soil map is a map

of soil profiles. The soil profile must be taken into account in devising the classification on which mapping methods are based. It would be useless, or almost useless, simply to map the texture of the surface soil, producing thereby a map showing the occurrence and distribution of clays, loams, sands, etc.

Now, if all the soils of the world had been studied, it might be possible to arrange them into a classification, comparable with the classifications of plants or animals. In an earlier letter I tried to outline the characters of some of the principal world groups. These might be regarded as comparable with the natural orders in the plant world, and we should be very content if we were able to construct a soil map of the world showing the distribution over its surface of these world groups. But when we come to the soil map of a single country, more information is needed. A soil map of Great Britain would carry only about half-a-dozen of the world groups, and within each group there would be variations that would be of considerable importance in practice, and a more detailed classification would be required. If it were a question of a map of a small area, such as a farm or estate, still more detailed classification might be needed, and one could even refine classification to the point of showing variations in the soil of a single field or garden.

Soil survey is in progress at a limited number of centres in Great Britain, but expansion in the future is likely. The methods actually in use have been adapted to British requirements but are

based on those used in the United States Soil Survey, in which the unit of classification is the *soil series,* defined as a group of soils developed from the same or similar parent materials under similar conditions and showing similar profile conditions.

No one who has studied British soils, whether from the theoretical or the practical standpoint, can fail to notice the important part played by geology in determining soil characters. And when I say geology I do not mean simply the stratigraphical position of a geological parent material, but its lithological character. Thus, the geological description Old Red Sandstone may include impure limestones, quartzose grits, and clay shales. It is the actual character of the rock that is significant. In British Soil Survey work, therefore, we group our soil series in relationship to the parent materials from which they are derived. I can explain this best by giving an actual example. Let us take the hard non-calcareous sediments of the Cambrian, Ordovician, and Silurian formations. From the soil-forming standpoint, they appear to form a single class. Let us see what series we can obtain from them.

Where the soil is formed by weathering of the rock in place, we get the Hiraethog* series and the Powys series. The Hiraethog series is the podsolized soil occurring under heath vegetation in waste areas; the Powys series is a non-

*It is usual to name series after the places in which they are first studied or where they have a wide development.

podsolized or slightly podsolized soil occurring generally under agricultural conditions, in Wales under permanent grass or under rotations with long grass leys. We may also distinguish a third series that is essentially the Hiraethog series from which the original A-horizon has been removed by erosion. Much of the soil of the better rough grazings lying just outside cultivation belongs to this series. The vegetation is generally of the *Agrostis* type with bracken. Where the parent material is deeper, as in boulder clay, glacial sands and gravels, and hill wash, other series occur. The Penrhyn series comprises deep well-drained soils, differing from the Powys series mainly by their greater depth. The Cegin series is distinguished by drainage impedance and may be sub-divided into three sub-series according to the degree of this impedance. The best Cegin soils are those that have been improved by pipe-drainage: they approximate to the Penrhyn soils. The worst Cegin soils are almost permanently wet and are uncultivable, occurring usually as areas thickly infested with rushes. Finally, there is the Conway series, consisting of soils formed in valley bottoms from alluvial material of similar origin to the parent material of the foregoing series. These are in many respects similar to the Cegin soils, and can be similarly sub-divided according to the wetness of the profile.

The examples given do not exhaust all the series that can be derived from the non-calcareous shaly parent material, but they include most of those found in the area occupied by this

parent material in the agricultural and marginal areas hitherto mapped.

Similar series can be derived from other parent materials, although not in every case is there such a variety. Complications are introduced by the occurrence of mixed glacial drifts. Indeed, most of the soil surveyor's puzzles in this country relate to the surface geology, which varies enormously and sometimes bears only a slight relationship to the solid geology as shown by the excellent maps of the Geological Survey.

In this country, the 6-inch to the mile Ordnance Survey maps are used as base maps and all field data are recorded on them, either by the use of an agreed system of symbols or by note-book descriptions with references to the map. The data collected and recorded fall under the following heads :—

A. Surface features and altitude. Most of this information is already on the Ordnance Survey maps, but it is convenient to record such categories as flat, rolling, steep, and broken.

B. Parent material. Under this heading the mode of origin, *e.g.*, weathered material *in situ*, boulder clay, hillwash, etc., must be recognized, as well as its actual lithological character, *e.g.*, basic igneous rock, non-calcareous hard shale, hard grey limestone.

C. Soil-water conditions. The distinctions under this heading are of great importance and can only be discovered by actual examination of soil profiles. Categories such as excessive drainage

(dryness), satisfactory drainage, seasonal wetness, and permanent wetness, are recognized.

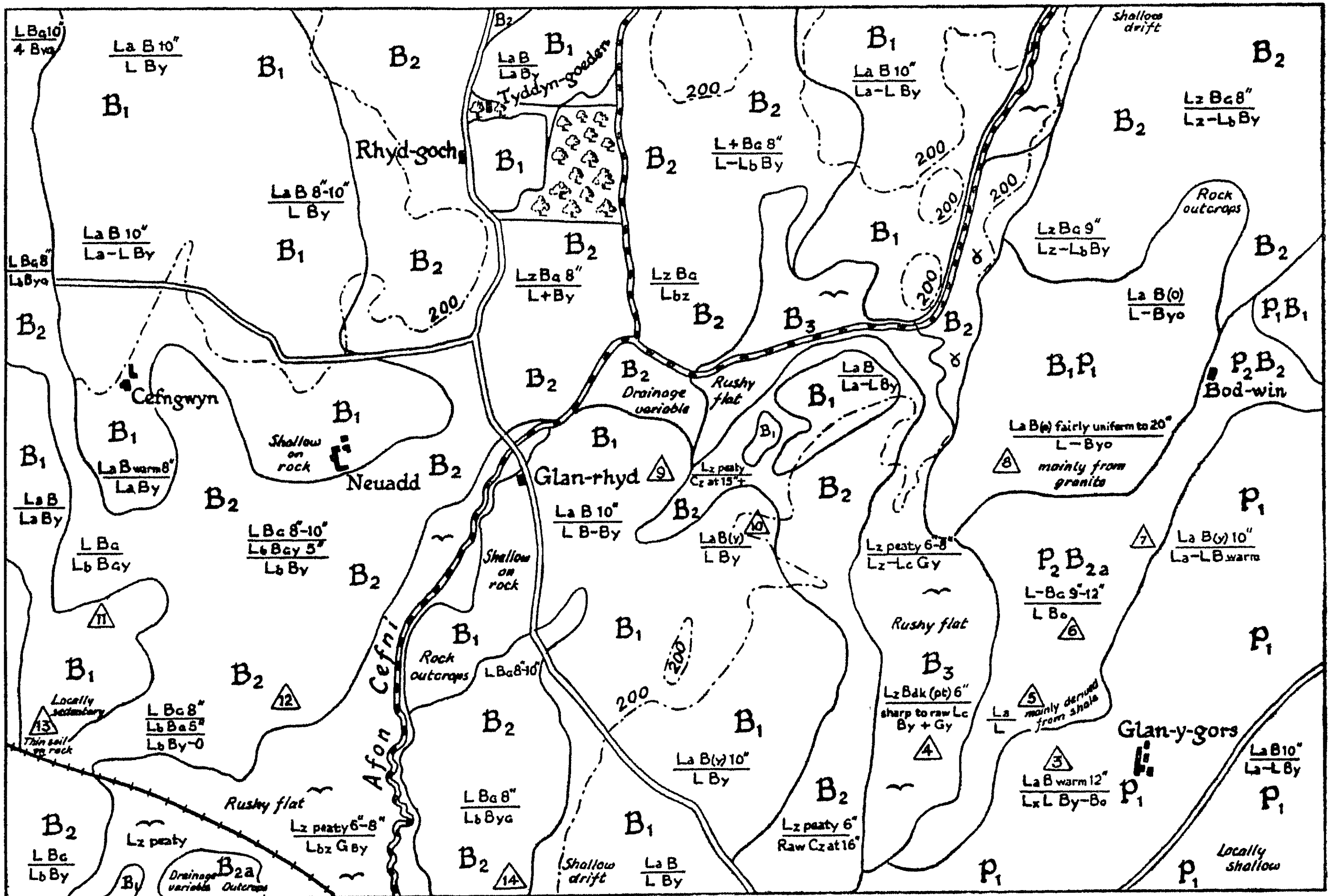
D. Depth and succession of the soil horizons. These are examined in pits dug at representative places. Uniformity of profile over an area is checked by means of auger borings, which also serve to indicate a change of profile as they are extended across the face of the country surveyed.

When a profile pit is opened, generally to a depth of about three feet, or until the parent geological material is reached, a vertical face is examined and the different horizons are distinguished. The depth, together with data for texture, colour, structure, compactness, etc., are recorded for each horizon. In addition, the character of the superficial humus horizons, if present, and the reaction (obtained by means of an indicator) are recorded. Note is also made of any occurrences such as concretions, mottlings, or stainings. In regions where calcareous parent materials occur, the acid bottle is used to verify the presence of calcium carbonate.

E. Natural vegetation and cropping. In waste lands, this means a general description of the vegetation. In agricultural lands, notes on the herbage (if grass) or the crop are made.

When a pit is opened out for the purpose of accurate profile description, samples are taken from the different horizons and these are examined analytically in the laboratory. The data serve to give precision to the observational data recorded in the field and also to define the different series in

SOIL MAP OF ANGLESEY. SECTION OF O.S. SHEET XIII. N.W.



Surveyed 1933 by D. O. Hughes and W. G. D. Walters. Based upon the Ordnance Survey Map with the sanction of the Controller of H.M. Stationery Office.

FIG. 7. Portion of 6″ to mile soil map of Anglesey. B1, Arvon series; B2, Eivion series; B3, Briant series; P1, Penrhyn series; P2B2, mixed Eivion and Cegin series. Figures in triangles refer to notebook descriptions. Field descriptions also given by symbols, *e.g.*, $\frac{\text{LaB}10''}{\text{LB—By}}$ = 10″ of brown light loam over brown to yellowish-brown loam. Contours —·— 200 —·—.

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quantitative terms. The identity or difference of profiles recognized in the field often depend on the interpretation of laboratory data.

In *Fig.* 7 you have an example of a typical soil map* as made in the field. The letters, *e.g.*, B_1, refer to the soil series, whilst the formulæ give the general characters of the soil profile at different points. The numbers in triangles refer to pits that have been accurately described and sampled for laboratory examination. From the 6-inch maps, generalized maps on a smaller scale are prepared. In the Frontispiece is an example of a generalized map, showing the soils of Anglesey.†

With your utilitarian bias I can imagine that you will want to know what is the value of these soil maps. Or, to put the question more generally, what is the value of a Soil Survey? And first, I will tell you what you must not expect from a Soil Survey. You must not expect a soil map to give you the manurial status of every field so that you can tell at once what manures and fertilizers it needs. This is impossible, for two reasons: firstly, because time would not suffice for the collection and analysis of soil samples from every field; and secondly, because such data would only have a temporary value and would change with vicissitudes in cultivation, cropping and manuring.

What we aim at showing on a soil map is the occurrence and distribution of the different kinds of soils, having regard to their permanent characters and not to those characters that can soon be

* I am indebted to my colleague, Mr. D. O. Hughes, M.Sc., for this map.

†Reproduced by kind permission of the "Welsh Journal of Agriculture."

changed by manuring or management. Thus, a soil of, let us say, the Penrhyn series might be changed by good management and liberal manuring from a low into a high condition of fertility. Similarly, continued neglect and exhaustive cropping without adequate manuring might so deplete the plant-food status of a fertile soil that crop returns would not repay the labour of cultivation and seeding. Such changes are temporary and do not affect the permanent character of the soil. There are, nevertheless, cases where long-continued treatment may alter essential soil characters. For example, when land has been for generations under grass it will acquire characters that will distinguish it from the same soil under continuous arable cultivation. Light sandy soils long under market garden culture, with heavy dressing of organic manures, will also change from their original character. The same may be said of changes consequent on artificial drainage. Thus, whilst short-term changes mainly affecting manurial status are disregarded for survey purposes, more profound changes consequent on long-continued treatment are recognized as sufficiently important to form the basis of series differentiation.

The information that can be conveyed by a soil map will be made clearer if we take the series that I enumerated in the earlier part of this letter and see what can be said of their agricultural properties.

Hiraethog Series. Poor podsolized shallow stony soils under heath vegetation. In their pre-

sent state suitable only for rough sheep-walk or grouse moor. Might be reclaimed, but the initial expense would be fairly heavy owing to the cost of clearing the rough vegetation and giving initial dressings of lime and phosphate. Would be only third-rate land after reclamation owing to the shallowness of the soil and the liability to drought.

Powys Series. Shallow, stony, generally light-loams. Less acid and peaty than the Hiraethog series. Second-rate arable and grassland. Liable to drought. Permanent grassland, if neglected and allowed to fall in lime-status, tends to a poor grass-heath type.

Penrhyn Series. Moderately deep to deep well-drained, generally stony, light to medium loams, carrying fair to good arable and grassland, depending on management and maintenance and on depth. Lime-status needs attention.

Cegin Series. Medium to heavy rather stony loams, naturally with poor drainage but often improved artificially. The improved soils are moderately fertile under arable but may give trouble owing to wetness in the spring. Grassland fair to good, depending on management. The unimproved soils of this series are rushy pastures only suitable for summer grazing. Suitable for improvement by drainage.

Conway Series. Alluvial soils varying from light stony loams to heavy loams, but generally heavy silt loams. Occasionally arable, but generally permanent grass of fairly good quality.

Similar to the Cegin series. Subject to winter flooding.

One could, of course, say more about the agricultural characters of these series, but I should like to emphasize the need for investigation, following up, and in the light of, the soil survey. The next stage after mapping should be the location of permanent experiments on the more important soil series. Most of the field experimentation hitherto has been carried out without accurate specification of soil characters. If, in addition to the permanent experiments on the most important series, all the available information on agricultural performance of soils of each series could be collected and analysed, the soil survey would acquire its full usefulness.

From what I have said you will gather quite rightly that, even where soil surveys have been made, much remains to be done before they can achieve their full possibilities. The soil map is only the first stage: it must be followed up by further work to interpret it in terms of the actual and potential performance of the soils which it represents.

We have heard much recently of planning British agriculture. The Soil Survey, in its fullest sense, is an inventory of our agricultural resources. But the soil map alone is only the first stage in this fuller survey. The task is of no small magnitude and should therefore be taken in hand without delay.

Ever yours,

G. W. R.

Letter XIII

ARABLE, GRASS, AND FOREST

My dear Stapledon,

I had intended at first to write this letter mainly on the subject of grassland, but lest it might appear presumption in venturing to address a grass expert on his own subject, I have somewhat widened the scope. I am sure that much of what I am about to say will already be familiar to you, perhaps so familiar to you that you may even disagree with it.

In spite of the increase in arable during the war years, grassland is still very much to the fore. And, indeed, its importance for our agricultural economy can hardly be exaggerated. We are pre-eminently a grassland country. Grass is our most important crop—how neglected, you yourself know only too well. It is, therefore rather curious that the natural vegetation of this country should be mainly forest or scrub. Even in our best grazing areas, the withdrawal of the influence of man and his grazing animals would eventually

be followed by the re-establishment of trees and bushes. Our grasslands are therefore artificial and this applies even to our rough grazings. I suppose our only natural grasslands are the downlands of the chalk and other limestone formations, coastal headlands, where trees are held in check by exposure to sea winds, and the saltings of our tidal lands.

The earliest arable cultivations were probably on soils that were naturally well drained, but with the coming of artificial drainage, marshes and swamp lands were brought into agricultural use. We may say, however, that our present-day grasslands are mainly the successors of the rough natural grazing that established itself on land either temporarily or permanently out of tillage. There is probably little grassland outside the natural grassland areas mentioned above that has not at some time been under the plough.

I must now get back to my own proper element, the soil, and I will try to set out what appear to me to be the essential features of forest, grassland, and arable soils. But before I do this I want to refer to some important differences between virgin soils and soils that have been exploited by man. In a virgin soil, whether under forest, heath, natural grassland (steppe or prairie), or desert, a condition of equilibrium and stability has been attained that is, apart from secular changes, little subject to alteration. Plant nutrient status remains at a steady level, at which the plant food abstracted from the soil by each season's

growth is returned as forest leaf-fall or the residues of herbaceous and grassy plants, the amount of plant growth being regulated by the moisture and plant food available. The profile of the soil consists of a layer of partially decomposed plant remains passing through a humified layer to the soil itself, which has a well-developed structure, at any rate, in its upper layers. In consequence of this structure and the humic character of the immediate surface, rainfall is readily absorbed. There is, therefore, little erosion and a stable soil profile is developed.

This stability, which obtains in virgin soils, is disturbed as soon as Man begins to play a part. Deforestation alone is sufficient to alter the character of the soil, but unless it is followed by arable cultivation the change usually results in the establishment of a new equilibrium that may slowly work back to its former position if reafforestation takes place. I may mention two instances of the kind of change that may follow simple deforestation.

(*a*) Deforestation, by immediately cutting down losses by transpiration (fly-off), in some cases leads to swamp conditions developing. Where forest is again established, these conditions gradually pass away as greater demands are made on soil moisture.

(*b*) There are many instances where, after the clearing of forest, heath vegetation establishes itself, with consequent deterioration of the plant-nutrient status and a profound change in the

character of the soil profile. Much of our sandy heath land was formerly under deciduous forest (oak, birch, etc.). Although the base-status was rather low, the constant return of leaf-fall, coupled with the comparative dryness consequent on the transpiration by forest vegetation, prevented that extreme deterioration that is evidenced by the development of a podsol profile. After clearing, the cutting down of transpiration induced greater leaching, whilst the heath vegetation, with its meagre plant food demands, kept a smaller quota of mineral nutrients in circulation. With the fall in base-status, raw humus developed, and a podsol profile replaced the brown earth or grey-brown podsolic profile of the original forest.

Before considering further the changes consequent on bringing virgin soil into cultivation, it will be desirable to compare soil conditions under forest with those under natural grassland. The differences are ultimately traceable to climate, forest being associated with humid, and grassland with sub-humid and semi-arid climates. At the transition from forest to prairie or steppe we can easily study the soil differences under similar climatic conditions. The most important, and perhaps the most surprising difference, is in the organic matter status, which is markedly higher under prairie or steppe than under neighbouring forest. In the forest, the organic matter content falls off sharply from the leaf-litter layer, particularly so under coniferous forest. Under grassland, the highly developed root system within

the soil, and the abundant seasonal contribution of plant residues to the surface, result in a well-marked dark humic horizon.

Associated with these differences are marked differences in base-status. These are due partly to the drier climate of grassland, which results in less leaching, and partly to the generally higher mineral requirements of herbaceous and gramineous vegetation, which have the effect of keeping more plant nutrient material in circulation within the upper horizons.

The contrast between grassland soil and forest soil becomes even more pronounced as we pass away from the forest-grassland boundary. In the direction of increasing dryness, the organic matter content gradually falls off, whilst the more arid conditions result in more scanty leaching. This incomplete leaching is reflected in the development of horizons of calcium carbonate deposition, which become more strongly developed and approach more closely to the surface as drier regions are reached. The same conditions also account for an increasing tendency for salt-bearing soils to occur as local phenomena.

Under forest conditions, increasing humidity is reflected in a progressive fall in base-status and the replacement of deciduous by coniferous forest. The rapidly decomposing litter layer of deciduous forest becomes replaced by needle litter overlying peaty humus, associated with a podsol profile (p. 68). Deterioration in base-status is accompanied by deterioration in structure. Whilst the

profile under deciduous forest is granular or fine-cloddy, conformable with a fairly evenly distributed mild humus, in the podsol profile, the raw humus layer is succeeded sharply by a loose dusty horizon poor in organic matter, overlying an horizon that is more or less compacted by precipitation of sesquioxides, ferric oxide, and alumina, leached out from the upper layers. In some cases there is a compacted humic-ferruginous horizon, which may cause drainage impedance.

Now, let us consider the agricultural utilization of these soils, and for this purpose we will consider four points in our range from humid to arid—in a mid-latitude, so as to exclude tropical soils, on the one hand, and arctic or sub-arctic soils on the other. The four cases I propose to consider are the following:—

(1) Coniferous forest associated with a podsol soil profile.
(2) Deciduous forest with brown-earth or brown forest-soil profile.
(3) Tall grass with prairie soil profile.
(4) Short grass with tshernosem (black-earth) or chestnut-earth profile.

(1) Consider first the podsol under conifers. The salient features are its low base-status, which, of course, means strong acidity, and its surface layer of raw humus. We may also notice the loose structure of the horizon below the raw humus layer. Such a soil, even if utilized in an "acid" type of husbandry for such crops as potatoes, oats, and hay, would demand initial dressings of

lime, chalk, or ground limestone to correct the deficiency of lime and the strong acidity, and also to promote crumb formation. Such a soil would probably be deficient also in available phosphate and require heavy phosphatic fertilization for good crops to be possible. When brought into cultivation, it would need regular applications of lime or similar dressings to make good wastage by leaching. The high rainfall would be favourable to plant growth and would permit a grassland type of husbandry. But constant attention to manuring (including liming) and management would be necessary to prevent degeneration. In short, we have here the conditions that obtain in the wetter districts of Wales—a grass country, but only on conditions.

(2) The profile (brown earth) under deciduous forest has a better base-status, conformable with the drier climate. There is an absence of peaty humus and the structure is better than in the first case. Such a soil would probably yield good crops immediately after reclamation from forest. The drier climate would render arable husbandry with grain crops a less anxious undertaking than under the wet climate of the podsol. At the same time, however, the rainfall would be sufficiently high to impose the need for attention to lime-status, particularly if the parent material should be naturally non-calcareous. Originally containing less organic matter than the podsol soil, the brown earth may be in danger of depletion in this constituent under continuous arable cultivation.

This would entail a deterioration in structure and the possibility of losses of valuable surface soil by erosion if periods of intense rainfall are liable to occur, as in parts of the United States. Whilst the climate is not humid enough to favour entirely grass husbandry, temporary leys in the arable rotation are feasible and may serve to maintain the organic matter status, with good effects on soil structure. This case is essentially that of the freely-drained soils of southern and eastern England and Scotland.

(3) The prairie soil, developed under tall grass, has a fairly high base-status, high organic matter content, and good structure. Brought into cultivation, it immediately yields good crops, which are well maintained under continuous arable cultivation, with well-chosen rotations and adequate manuring. Loss of organic matter is a danger under the comparatively dry climate and the return of organic matter to the soil should be rendered possible by the keeping of live stock. Lime may be necessary after long cultivation. The climate is favourable for cereals, but, although the natural vegetation is grassland, artificial grassland is hampered by recurrent droughts.

Soils of this type occur in the United States in Illinois, Iowa, and Eastern Kansas. Although the climate is only moderately humid, intense rainfall may cause erosion in soils which have lost structure through depletion of organic matter.

(4) Finally, there is the case of the black-earth soil originally under short-grass cover.

Here the organic matter and base-status are high and the structure is excellent. Good crops are obtained immediately and are well maintained without the need for dressings of lime. Yields will be lower than under prairie soil conditions owing to less moisture being available, and there is a greater risk of crop failures through drought. For the same reason, artificial grassland of high quality is difficult to maintain. Where stock is kept, it is possible to return some organic matter to the soil. Otherwise there is a danger of progressive depletion, and the consequent loss of structure exposes the soil to the danger of wind erosion.

The cases that I have briefly reviewed represent points in a range of soil conditions. We in Wales fall between cases (1) and (2) for the most part, with a tendency towards case (1) in our wetter districts and towards (2) in our drier districts. The moral of it all for Wales is this: Grassland is artificial and cannot be maintained except by care and attention. Arable culture is beset by equal difficulties and many limitations on account of the wet climate. Experience plus science have taught us the necessary care and attention to be used for the maintenance of grassland: they have also taught us to observe the limitations and to overcome the difficulties of arable culture. And thus we arrive at what is essentially, I think, the Stapledonian doctrine. We can maintain good, even excellent, grassland if we combine it with arable in the typical Welsh rotation, three years

under plough and x years under grass ley. But we must pay attention to our lime status and our phosphate status; above all our lime status, for about 2 cwt. of lime per acre is lost annually from typically Welsh soils, mainly in drainage waters. Otherwise, our arable crops will be unsatisfactory and our temporary leys will be difficult to establish and will rapidly deteriorate. We must also choose our seed mixtures wisely and we must practise rational management of our temporary grassland when we have it.

If the arable break is the salvation of our grassland, the temporary ley is the salvation of our arable. During the years under grass the soil is accumulating precious organic matter, not the sour peaty humus of degenerate *Nardus** swards, but the living humus that is the storehouse of fertility, the humus by means of which the soil recovers the structure which it has lost during the arable break.

But I would go further and preach the temporary ley wherever the plough works. In the classical four-course rotation of the arable districts of England, would not the substitution of a two- or three-year ley for the one-year clover and rye-grass raise the general level of fertility and, by raising the organic matter status, improve the soil structure with consequent easing of tillage operations?

The temporary ley might have been, and might still be, the salvation of agriculture in other lands.

**Nardus stricta*, mat-grass.

I remember watching a team of sixteen oxen laboriously working an intractable clay in the sugar lands of Trinidad. In all probability, when that land was first broken generations ago, it had the good structure of a virgin soil. Then, with constant cultivation, the organic matter ran down, the structure was destroyed, and the original surface soil was probably removed by erosion. And I thought that, if some wise agronomist, foreseeing all this, could have devised a method of making a temporary ley, both soil and structure might have been retained. Temporary leys might have saved millions of acres of lands in the United States now in ruins through erosion.

But these are empty regrets because, in colonial days, nobody was alive to the perils of soil destruction, and even if they had been, they could not have used temporary leys. Neither can they, even in this twentieth century, in many lands where such a practice might be of incalculable benefit. Here, then, is a task for you agrostologists. Realizing, as you ought, the immense advantage of laying up land in ley, it would be a worthy object to discover or breed for every region appropriate plants, not necessarily grasses, for the formation of swards, and to devise agricultural methods for the establishment of such swards. Is it too much to hope that some day it may be possible to lay up the heavy clays of the Trinidad sugar fields, and similar soils in other lands, in their own particular versions of our temporary leys? It is true that work on forage plants is in

progress, but I think it would acquire added impetus if it could be realized that pasture has a wider significance than merely as a food for stock, and that it may form an integral part of a permanent system of agriculture.

Ever yours,

G. W. R.

Letter XIV

OUR AGRICULTURAL SOILS

My dear Stapledon,

There is as yet no official soil map comparable to the geological map of Great Britain, published under the authority of the Geological Survey. Soil surveys are in progress at a few centres, but systematic knowledge has still to be collected for a large part of the country. I can only give, therefore, general impressions of British soils based on existing surveys and on my own impressions gleaned in travelling to and fro. I wish it were possible to give a soil map, but that remains for the future.

Let me remind you of some of the main factors determining the character and distribution of British soils :—

(1) The surface of Great Britain shows all gradations from the mountainous areas of the north and west to the flat areas of the south and east. This is only a broad generalization, for flat areas may occur in coastal flats in the north and

west, whilst hilly areas, such as the chalk downs, may occur in the south and east.

(2) The geology is equally diversified, and we find rocks of all ages from pre-Cambrian to Recent. Again, there is a contrast between the north-west and the south-east. The most ancient rocks occur in the Highlands of Scotland and in north-west Wales. As we pass south and east we cross successively more recent formations, reaching the Tertiary formations of the East Anglian Coast, the London Basin, and the Hampshire Basin. The older rocks are generally hard, being either igneous rocks or sedimentary rocks that have undergone considerable induration and even metamorphism, so that soils derived from them are formed by primary weathering (p. 59). The newer rocks are generally sedimentary and have undergone no great degree of metamorphism, so that soil formation is by secondary weathering.

Associated with the different geological formations are superficial deposits derived from them, such as glacial drifts, hill-wash, and alluvia. These derived deposits are more or less distant in place from their parent rocks and are often of a mixed character. Thus, whilst in Anglesey the glacial drift overlying pre-Cambrian rocks has generally a schistose character, the chalky boulder clay of East Anglia contains Kimmeridge Clay derived from the outcrop of that formation many miles to the west.

(3) Whilst the climatic conditions of Great Britain can be generally described as equable and

humid, there are contrasts. Again, we may contrast the north and west with the south-east. On the Atlantic side, we have high rainfalls, mild winters, and cool summers; on the continental side we have a drier, though still humid, climate, with warmer summers and colder winters.

(4) The soils of Great Britain have been largely affected by human interference. The land under crops and grass amounted in 1938 to about 70% of the area in England, 54% in Wales, and 24% in Scotland. Since then the arable area has grown, but it is probable that if and when more normal times come round, grassland will again expand. All this land has been profoundly altered from its primitive condition, which was mainly forest, scrub, or swamp. But much of the land in hill and rough grazings has also been modified through the replacement of forest by grazing lands and the changes consequent on this replacement.

The freely-drained soils of Britain range generally between podsols (p. 72) and brown earths (p. 74), with modifications induced by agricultural utilization. Whilst much of the podsolic soil may be thus described without qualification, most of the brown earths are more correctly described as *agricultural brown earths*. Among these may be former podsols changed to brown earths by cultivation.

Soils derived from calcareous parent materials must be specially considered. Where, as is the case with most of the chalk soils, calcium car-

bonate is still present throughout the profile, soils may be assigned to a class known as *rendzinas* or *humus-carbonate* soils. Cultivated chalk soils might be described as *agricultural rendzinas*. Where carbonate has been leached from the soil profile, as is the case with most soils derived from hard limestones, such as the Carboniferous Limestone, the soils approach more nearly to the brown earth character. Certain red soils over limestone may have affinities with the terra rossa of Mediterranean lands.

Soils with impeded drainage fall mainly into the class of gley-soils (p. 80). With them we may group soils which were formerly podsols but in which the development of an impervious horizon has induced drainage impedance. Such soils are termed gley-podsols (p. 81). Gley-soils have been considerably modified by artificial drainage and in many cases approach the brown earths in character. Gley-soils are characteristically developed on the clay formations, such as the Lias, Kimmeridge, and Oxford Clays. They also occur in lowland flats with regional water-tables. With the gley-soils we may group the peat soils of the Fens. Other peat soils fall generally into the soils of waste lands, although they are occasionally found under cultivation, as in Chat Moss in Lancashire.

Having disposed of these preliminaries, we shall find it most convenient to consider our soils according to their geological origin. Although geology does not form the basis of a world-classi-

fication, yet within our own country soils can be well arranged according to the parent materials from which they are derived. I propose to consider them, not strictly accordingly to geological formations, but rather according to actual rock materials.

The pre-Cambrian and Lower Palæozoic rocks (Cambrian Ordovician, and Silurian) and the igneous rocks are generally non-calcareous crystalline or hard sub-crystalline. They give rise, therefore, to soils of primary weathering. Although there are differences, we may conveniently consider them together, since they occur most commonly in the mountainous or hilly regions of Scotland, N.W. England, and Wales, under generally high rainfalls. Most of their area is occupied by uncultivated hill or mountain land. The agricultural soils of the lowlands are mostly derived from glacial drift material and hill wash. In Wales and southern Scotland, they are predominantly grassland soils, sometimes of good, but often, owing to neglect, of inferior quality. In Wales, large areas are in rushy pasture with impeded drainage. In north-east Scotland, freely drained soils derived from drifts form good arable soils that owe much to good management, assisted by a fairly dry climate.

The Old Red Sandstone gives rise to soils that are generally better than those of the preceding group. Both in Scotland and in Wales, these soils stand out favourably by contrast with adjacent soils derived from more ancient parent

rock materials. Indeed, their occurrence is generally betrayed by the more genial aspect of the countryside. This is due to the fact that they are more highly weathered and deeper, and also to their rather better lime-status. In the west Midlands of England, soils of the Old Red Sandstone are much used for orchards. The famous red lands of Dunbar in Scotland are mainly derived from Old Red Sandstone material.

The Carboniferous Limestone gives rise to thin upland soils used for sheepwalk and also to deeper lowland soils, which are often of considerable fertility, owing to their texture and the presence of calcium carbonate. Actually, however, the greater part of the area occupied by this formation is in the upland type.

The Millstone Grit is mainly represented by acid upland soils in heath or moor. The lowland soils are generally but not always rather light in texture and prone to acidity. The rocks of the Coal Measures give rise to variable soils, some of which, for example, those derived from the Pennant Grit of S. Wales, are poor upland soils. The derived drifts in Northumberland and south-eastern Scotland are often well-farmed fertile soils under grassland or mixed husbandry. There are also considerable areas of rather poor soils with impeded drainage.

The Trias occupies a considerable area in Central England, extending up through Lancashire on the west and through Yorkshire on the east of the Pennines. It also extends south

through western England to Devonshire. The derived soils are almost entirely under agriculture, the only considerable area of waste being Cannock Chase in Staffordshire, where the light podsolic soils are derived from the Bunter Pebble Beds. The lighter Triassic soils, derived from Bunter and Keuper Sandstones and their drifts, are essentially soils that depend on good farming. At their best they include, in Shropshire, some of the mostly highly farmed land under mixed farming. But they also include poor hungry soils that readily revert to heath. The heavier soils associated with the Keuper Marls are usually under grass. The dairy grounds of Cheshire are mainly soils of the Keuper Marl boulder clay. The Keuper Marl can also carry good orchards in Worcestershire, Gloucestershire, and Devonshire.

The great variety in lithological character in the Jurassic and newer rocks introduces a corresponding variety in their derived soils. The harder Jurassic limestones give rise in the Cotswolds to thin reddish soils, now generally used for sheep pasture, but they carry good farmland where the surface relief permits the accumulation of deeper soils. Much of the Chalk is also in upland sheep pasture, but there are also large areas, for example, in E. Yorkshire, Lincolnshire, Hampshire, and Sussex, under arable cultivation. The soils are generally thin, and are highly calcareous. Deeper soils occur at the foot of slopes and in hollows. Chalk soils are particu-

larly liable to drought, though not to the extent that might be expected from their scanty depth.

The clay formations of Jurassic and later age give rise to a considerable variety of soils, a variety that may be partly explained by the presence or absence of calcium carbonate. The Lias clays carry the famous pastures of Leicestershire; they also furnish fruit and market garden soils in the Evesham and Pershore district. Yet they can also carry poor derelict pasture tumbled down from former wheat lands.

The Oxford and Kimmeridge Clays of the Jurassic, the Gault and Weald Clays of the Cretaceous, and the London Clay of the Tertiary, furnish heavy and often wet soils, some arable, but with much poor derelict pasture. The lighter types, particularly when there is an admixture of sandy drift, are more tractable, and are of fair repute for mixed farming.

The Boulder Clays of East Anglia form a wide range, depending on the parent formations that have contributed to them. They show gradations from comparatively light, tractable soils, to the heavy clays of Cambridge and Essex, now mainly under poor pasture, but sometimes considerably improved by the skill and industry of immigrant Scottish farmers. The reddish Clay-with-Flints, found overlying the chalk, gives moderate soils, which have often been improved by dressings of the underlying chalk. Lying generally in elevated situations, they are not always so prone to wetness as soils of some of the other clay formations.

The newer sand formations occupy a smaller area than the clays and limestones. We may distinguish two classes. In the first class we have soils derived from materials like the Lower and Upper Greensand, containing a reserve of weatherable minerals such as glauconite, whilst in the second class are the highly quartzose sands of the Tertiary, such as the Bagshot Sands, and the glacial sands and gravels. The former, whilst not exempt from the anxieties attendant on sandy farming, are of moderate fertility, and even include cultivated market garden soils, such as those of the Potton and Biggleswade district of Bedfordshire. The second class of sandy soils are considerably poorer as agricultural land and include considerable areas of heath in the Breckland of Norfolk and Suffolk, the Surrey heaths, and the New Forest.

Finally we must note the highly farmed soils developed from recent estuarine alluvia and peats of South Lincolnshire and the Fens. These are among the most highly farmed arable soils in Britain. Their excellence may be attributed to their good lime-status, their fine sandy or silty texture, their depth, and the skilful artificial control of their drainage.

I have written superficially, and, it may be, inaccurately, of the soils of our country. The soil map of Britain does not yet exist. At the present rate of progress it may be a heritage for our great-grandchildren. But even if such a map were before me it would still be almost

impossible to epitomize the almost infinite variety of our soils in a few pages. Look at the Geological Map and note the intricacy of outline of the formations represented. The soil map, when it is made, will not be less intricate. Can it be said that Nature has been generous to us in our soils? If by fertile soil is understood soil that will give crops year by year without exhaustion, simply in return for tillage and seed, we have no fertile soil. We have no Nile to fertilize our fields year by year. But if by fertile soils we mean soils that will give a generous return for skilful labour, and that will still give the same rewards to future generations, then I say that I know of no land that I would take in exchange for our own.

Ever yours,

G. W. R.

Letter XV

WASTE LANDS

My dear Stapledon,

You have studied waste lands for many years and have written about them with great effect. You have shown how they may be brought to greater productivity. I can only tell you the soil side of the story, and this I propose to do in the present letter. Most of what I have to say will concern the soils of the inland wastes, but I shall also have something to say about the coastal wastes, which are conveniently considered separately.

Let us hark back to the subject of rock weathering. Rocks exposed to atmospheric influences undergo weathering and decomposition, and it is from the products of this weathering and decomposition that soils are formed. Now, if there were no removal of the products of weathering, these would accumulate in place and form a deepening mantle of material which might eventually become so thick that the underlying rock would be protected from further attack by atmospheric influences. But actually, there is always a movement of material downwards to

lower ground and eventually into rivers, which carry it down to the sea. By this process of denudation, the land surface is gradually worn down. If it went on indefinitely without the intervention of any great earth movements of uplift or depression, the continents would eventually be worn down to a dead level. The thickness of weathering material depends on the balance between the processes of weathering and denudation. Where weathering is rapid, as in the humid tropics, or where the rock is readily weatherable, like soft sandstones or certain kinds of volcanic ash, the tendency will be for the weathered layer to be deep. On the other hand, where weathering is slow, as in polar or alpine climates, or where the rock weathers slowly, as in the case of quartzites or acid igneous rocks, the tendency will be towards shallowness in the weathered layer. Deepness in the weathered layer is favoured by slowness in denudation, which obtains where gradients are very gentle or where rainfall is light. The weathered layer will tend to be shallow where gradients are steep and where rainfall is intense. Deep layers may occur at the foot of steep slopes where accessions of material from higher ground preponderate over losses by transport to still lower levels.

Now, in our uplands, we have steep slopes, high rainfall, and, frequently, hard rocks. Hence we get shallow soils. Indeed, in rocky areas, the balance between weathering and denudation is so unfavourable that there is often no soil at all.

Whilst we may say that our upland soils are generally thin, owing to the unfavourable balance between weathering and denudation, we find deeper accumulations in areas of concave relief (hollows) and at the foot of steep slopes. With convex relief, soils are invariably shallow, apart from peaty accumulations.

In considering our British upland soils, we must not leave out of account their past history. It is supposed that forest formerly extended up to about 1,700 feet in southern Britain. Now, a forest cover would have a considerable influence in slowing down denudation, and consequently favouring soil depth. In the interval between the removal of forest by man and the establishment of grassland, denudation was probably fairly rapid, amounting almost to erosion. We may conjecture that many of the rocky hillsides of Wales carried a certain depth of soil in their former forest condition, whilst there are large areas where, although the soil profile has not disappeared entirely, it is of a truncated type, the original A-horizon under forest having been removed, leaving what was originally the underlying B-horizon as the present surface soil.

And so, in our first consideration of waste lands, we may forget for the time about soil and think simply of this mantle of weathered material, thinning out, or even pierced by the underlying rock, in the uplands, and thickening in the lowlands and hollows. We must also think of the deposits left by the glaciers, spread out over our

lowlands and sometimes creeping up our hill-sides. These also have been moulded by running water when the ice left them. We must think of the way in which rivers have carried seawards the burden that they have received from the land, sometimes leaving them as alluvial flats along their courses, sometimes spreading them out as mud and sand in their estuaries. And we must also consider how the wind has blown sand from tidal lands, and spread it as dunes along our coasts.

To return to our soils: in upland regions with convex relief, not only do the soils tend to be thin and rocky, but they are also subjected to high rainfalls, highest of all in our mountain tops. These upland soils are strongly leached, not only because of the high rainfall, but also because of their shallowness. The leaching of six inches of soil over rock by sixty inches or more of rain will be more intense than the leaching of six feet of soil and sub-soil by the same amount of rainfall. And so these upland soils are bereft of nearly everything that can go into solution, and their mineral status is, therefore, very low. But the high rainfall favours the accumulation of a peaty humus layer at the surface. Upland soils, unless they are formed from parent material rich in lime, such as the chalk, are, therefore, not only poor in bases, but also very acid.

The poor base-status and the acidity in themselves limit the type of vegetation which can exist, but there is also the moisture factor.

Although upland soils generally occur in regions of high rainfall, their shallowness renders them liable to drought, principally because the development of deep-rooting systems is impossible, but also because moisture rapidly drains away from them. And so we get a type of herbage which must tolerate both acidity and drought. You will be able to confirm that such herbage will not include the more valuable grazing plants. You will also agree that if the best type of herbage could be temporarily established on such soils, it would not be able to survive the drought periods that are inevitable in such situations, even in wet Wales.

The tendency in well-drained upland soils is, therefore, towards a heath type of vegetation, and a soil profile of the podsol type. We do not, however, always get a typical podsol profile. The so-called "ffridd'"* lands, which occur above the present-day farm lands, often appear to be podsols from which the upper bleached horizon has been removed. It is probable that much of this removal took place by erosion after deforestation, and before the establishment of a grass cover. I think it would be correct to say that "ffridd" extends upwards only to the former limit of forest. I should assign your "heather fell" (heather, with fern, gorse, and scrub) to this soil group, but should give it an inferior position

**Fescue-Agrostis* pastures, with fern, gorse, and scrub invasion.

as to possibilities of improvement, because the soil is thinner and more rocky.

Above the "ffridd" we find heather moor, or mountain fescue pastures, with podsolic soil profiles. But heath with podsolic soil profiles may also occur at lower levels, and here, I think, it is likely that degeneration from an earlier "ffridd" type may have occurred. On parent materials, poor in basic constituents, such as the Millstone Grit of the Pennines, degeneration can occur more readily than on parent materials such as the older Palæozoic sedimentary rocks, and the Old Red Sandstone, and heath with podsol, therefore, occurs at lower levels.

But podsols can undergo transformation. You will remember that in podsolization there is an accumulation of ferric oxide and sometimes humus in the so-called B-horizon. This accumulation may proceed to such an extent as to cause an impedance of the drainage. The profile now becomes wetter, and the tendency is for peat to accumulate. Much of the land occupied by *Nardus* vegetation appears to have been formerly heath with podsol. For example, on Carnedd Dafydd, Caernarvonshire, about one foot of peat overlying what is essentially a podsol profile was found under a vegetation of *Nardus stricta*, *Festuca rubra*, and *Luzula campestris*. On an adjoining mountain, Y Drosgl, at 2,400 feet, about two feet of peat was found overlying a podsol profile, and under an almost pure *Nardus* vegetation.

In a more advanced stage of drainage impedance, the profile may become still wetter, and the peat development more pronounced. For example, at 3,000 feet on Foel Fras, Caernarvonshire, there is about three feet of peat under a vegetation of *Juncus squarrosus, Calluna vulgaris, Molinia cœrulea,* mosses, *Empetrum nigrum, Vaccinium myrtillus,* and *Nardus stricta.* Using the Aberystwyth classification of waste lands, I should say that these podsols, which have become wet and peat-forming, fall into the *Molinia-Nardus* group.

In upland areas of concave relief and at the foot of slopes, material accumulates to greater depths, and the tendency is for the profile to be wet. In such cases ground-water soils are developed, varying in character from gley-soils to peats. In flushes, where water percolation brings mineral material both in suspension and in solution from the higher ground, the soil, though wet, may have a fairly good mineral status. Such soils, though generally of very limited extent, carry a better herbage than the leached soils on the adjacent higher ground. These I would assign to your "flush-bog" type.

More frequently, these areas of accumulation form the foundations for the development of peat. Any surface which is permanently wet with waters containing only traces of dissolved mineral matter becomes occupied with vegetation such as sphagnum moss or *Scirpus* (deer-

grass) whose residues form peat. When peat has developed to a certain thickness, the "soil" moisture is practically rain water, because connexion with the mineral soil is lost. The mineral status then becomes very low indeed. These soils would probably fall into your "cotton-grass (including deer-grass) moor."

I now come to the wastes of the lowlands, and with the lowlands I include areas which, although at a high elevation among the mountains, occur in the bottoms of valleys. The lowland wastes include a variety of types, which I shall mention in order.

Most of the lower land in Britain, north of the Thames, is covered by glacial drift, that is to say, boulder clay and "sands and gravels," derived from the water-sorting of boulder clay. Much of this boulder clay has been improved by artificial drainage, and is now agricultural land, showing a wide range of productivity. Some of the boulder clay land, which was once improved, has lapsed through neglect to poor, rushy pasture.

There are considerable areas in North Wales, particularly in Caernarvonshire, that have either never been improved, or have lapsed so long from their improved condition that they are practically wastes. They are for the most part very acid peats of varying thickness, overlying light grey stony boulder clay. In many places the peat has been cut for fuel. The vegetational types vary from *Molinia-Nardus* to cotton-grass (including deer-grass) moor.

These soils, although occurring in the lowlands, have generally a slightly elevated topography. In the actual bottoms one finds two main types. The one type consists of lacustrine peat, which has been formed by the growing up of former lakes in the boulder clay. Unlike the fen peats of East Anglia, the Welsh lacustrine peats have generally a low lime-status, and do not offer the best prospects of improvement. Tregaron Bog is an example of this type. In some cases, the peat formation has proceeded past the lacustrine peat stage and has reached the poorer moor-peat stage. The vegetational types are cotton-grass and deer-grass moor with local *Nardus* and heather types on drier sites.

Another type of bottom land among the lowland wastes is that of alluvial flats. Here the mineral status may be better, owing to accessions of material washed down from the uplands, and one may find soils which, though very wet and rush-infested (*Agrostis*-rush pastures), show very slight peat development. One may also find intermediate types which, although essentially lacustrine peats, have some admixture of mineral material, and show a vegetational range from *Molinia-Nardus* to *Agrostis*-rush pastures, with local cotton-grass moor. The tract known as Cors-y-Bol in Anglesey is an example.

In the Survey of the Agricultural and Waste Lands of Wales, William Davies has arranged the principal pasture types in the following order of agricultural value:—

Group I.—*Molinia-Nardus.*
Group II.—Fescue-*Agrostis.*
Group III.—*Agrostis* (with fog, white clover, etc.).
Group IV.—*Agrostis*-ryegrass (with white clover, *Agrostis,* etc.).
Group V.—Ryegrass.

I believe you would admit that cotton-grass—deer-grass moor is poorer even than the *Molinia-Nardus* pasture. My comment on this series is that it exactly represents, on the soil side, an ascending scale of lime-status from the poorest, which is the cotton-grass—deer-grass moor, up to the richest, which is the rye-grass pasture. I think we may say, as a corollary, that the use of lime and possibly other minerals, including phosphate, may be expected to cause a shift of each type towards the better types.

In the foregoing account I have dealt with waste lands in which the soil is naturally poor in lime. For the sake of completeness, I should also mention the upland soils developed on calcareous parent materials, the principal examples of which are the chalk downs. Here the factor limiting productivity is drought, although it must not be forgotten that there are, even in downland areas, stretches of sandy or gravelly soil, poor in lime. Chalk downs are essentially sheep pasture, and are not generally suitable for arable cultivation, owing to their shallowness and liability to drought. Indeed, much of this land, if ploughed, would probably be subject to erosion

when the original structure had been lost. It is not improbable that such erosion may have occurred in the past, when attempts were made to bring them under arable culture.

Before considering the coastal wastes, I must mention a class of waste of which we in Wales have a comparatively small area. I refer to the sandy heaths, such as those of Cannock Chase in the Midlands, the Breckland of Norfolk and Suffolk, parts of the New Forest, and the Surrey heaths. From the soil standpoint, these are generally podsols in varying stages of development. The degree to which podsolization is shown depends to a large extent on the nature of the parent material. The Triassic sands appear to have a slightly better base-status than the Tertiary sands of southern England. The most strongly developed podsols that I have seen are some of those in Surrey and Hampshire. In these areas, I have also noticed the beginning of drainage impedance, owing to the development of an impervious B-horizon.

The sandy heaths of England are more attractive scenically than agriculturally. In some places, extensive afforestation has been carried out, but I have some doubt as to the ultimate result of exclusive coniferous planting. With their scanty mineral requirements conifers are, of course, adapted to soils with low mineral status; but, if they do not fully utilize such mineral plant food, there is a danger of further deterioration, with formation of raw humus, events which

may take a century or more to fulfil themselves, but which can occur, as has been found in certain regions in Germany.

It now remains to consider the coastal wastes, which fall into two main classes, namely, the estuarine alluvia and the coastal sands.

Estuarine alluvium, when reclaimed, is among the most valuable land, either for pasture or arable, witness the polder soils of Holland, and the famous Romney Marsh soils of Kent. It is probable that much more valuable land might be won from salt marshes at many points round our coasts by the methods that have been used in Holland. The heavier soils might be used for pasture as in Romney Marsh, whilst the lighter soils would be suitable for mixed arable culture. In the mild climatic conditions of the west, horticultural development is suggested.

The coastal sands show all stages from blowing dune to soils which have a closed cover of vegetation. They are not promising for ordinary agriculture, and I think we should both agree that Providence has designed them for golf links. In some places, however, the presence of ground-water may offer possibilities for market-gardening and bulb growing, particularly if the water-table can be maintained at a constant depth by means of drainage and pumping. Such soils are naturally poor in plant food and liberal manuring would be necessary.

Ever yours,

G. W. R.

LETTER XVI

CORRUPTIO OPTIMI PESSIMA

MY DEAR STAPLEDON,

Towards the end of Plato's Republic there is a solemn account of the Decline of Society and of the Soul; and I propose in this letter to say something of the "Decline of the Soil." I will illustrate this rather sinister subject by telling you something of the tragic happenings to the soil of the United States. They are not without parallel in other parts of the world, but nowhere else has the drama of soil destruction been played so swiftly and on so great a stage. The disastrous circumstances have forced themselves on the attention of the American people, and have obtained publicity even in this country. The fate of the soil of the United States has its lessons for us, perhaps not so much at home as in our overseas Empire.

When the white settlers first reached America, they found a country practically untouched by human activity. The scanty population of Indians hardly disturbed the natural balance of soil and vegetation. The eastern part of what is now the United States was mainly forest—

coniferous in the north and in the sandy soils of the south, deciduous forest elsewhere—with intervening swamps and coastal marshes. Favoured by the humid climate, the cleared forest soils, with their accumulated reserves of fertility, at first gave good returns. But it was soon found that fertility was not inexhaustible. Not only did yields fall off, but owing to the loss of the original crumb structure, or soil fibre, the soils became liable to water erosion, particularly since, in these regions, rain may fall in intense downpours.

Where erosion occurs, much of the fertile top soil is removed, and deep gullies may be cut, interfering with agricultural operations, and rendering soils liable to drought. Erosion tends to proceed at an ever-increasing pace, for exposed subsoil is even less able to absorb heavy rainfall than the original topsoil. The result is that water flows over the surface, still further washing material away and cutting down into gullies. These were the consequences of the exploitation of the soils of the Eastern United States.

Exploitation was not always attended with equally disastrous results. There were considerable variations in the liability of soils to erosion, whilst in some cases the type of agriculture practised was more conservative of soil resources. In this connexion, one American writer considers that the first Dutch and German colonists showed more skilful and conservative soil management than the British colonists, who simply mined the soil wealth. To-day, as one travels to and fro

across the lands settled before the Revolution, one gains the impression of a generally poor agricultural country, with great areas ruined by erosion, or lapsed to bush or forest. Even the more productive areas, particularly the cotton lands, are largely dependent on artificial fertilizers to maintain yields. Indeed, much of the soil for cotton and tobacco is little more than a vehicle for purchased fertilizers.

The decline in fertility of the older lands was not regarded as a serious calamity, for across the Alleghanies lay apparently limitless land for fresh exploitation, and the tide of settlement flowed west. The same drama of soil depletion and soil ruin was re-enacted in the Mississippi valley, but still more land lay to the west. Across the Mississippi, the settlers found even better soil in the prairies, but towards the end of the last century, settlement was practically complete. It had pushed past the tall-grass prairies to the high plains, with their short-grass vegetation. But beyond the prairies the climate becomes drier, and the risk of drought failures and wind erosion greater. It is now realized that the tide of agricultural settlement flowed too far in the direction of the desert, and that great areas in Oklahoma, western Kansas, Nebraska and the Dakotas should never have suffered the plough, but remained as range lands.

The mere working out of the accumulated fertility of virgin soil is a small matter compared with the losses by wind and water erosion.

Where land has been cropped to exhaustion, it is still capable of recovery. But where topsoil has been removed, and the surface cut into gullies, recovery can only take place in the space of centuries. It is damage by erosion that is the most serious consequence of land exploitation in the United States.

The loss of valuable soil by erosion is not the only aspect of this great calamity. Accounts of serious floods in the United States are familiar even to us: the Ohio floods of 1937 are still remembered. These can be attributed in a large measure to soil erosion in the catchment areas. Under natural vegetation or grass, soil behaves as a sponge, capable of absorbing rainfall and yielding it up slowly to the drainage, and thence to rivers. When the absorbent topsoil has been removed, heavy rain runs rapidly over the surface, swelling the rivers, and carrying into them a burden of silt. Flooding thus occurs with great rapidity. Nor is the evil confined to flood alone, for the silt washed from the land is carried down and deposited in the lower reaches. The bed of the Mississippi, the outlet of the interior of the United States, is, therefore, continually being raised. In order to confine it within a channel, artificial levees have been made, between which the great river flows high above the level of the streets of New Orleans. If the present state of affairs continues, it seems likely that the river bed and its accompanying levees must rise ever higher and higher. And the

higher the levees are raised the more work must be expended on them to render them safe.

Further to the west, on the high plains, soil destruction took another course. In the urge for expansion of the wheat-growing area, large tracts of range lands were brought under the plough. All went well for many years, but the structure of the soil was steadily deteriorating, parallel with the loss of organic matter. Then came the droughts of recent years, and vast areas of farm land went up in clouds of dust, which darkened the sky as far east as the Atlantic coast. Even where the range lands had not been broken by the plough, considerable damage was done by overstocking, which destroyed the natural cover with its stabilizing mat of roots, and exposed the bare, dry soil to the scour of the wind.

And so the great tragedy of soil destruction was enacted, in a little more than two centuries. The sequence is well understood—deforestation and cultivation of the cleared land; loss of organic matter and destruction of structural stability; the washing away of the topsoil by erosion, and the formation of gullies; rainfall reaching the river systems with ever-increasing rapidity; disastrous floods; and silting up of storage reservoirs and river channels. In the drier regions, the loss of natural structure exposes the soil to wind erosion. With our knowledge of the soil and its behaviour, it is easy to censure the reckless spoliation of the greatest wealth a nation can possess. Yet it was

not easy for the pioneer agriculturists to realize the consequences of their actions. And there was always the " concept of infinity " exemplified by Horace Greeley's famous advice—" Go west, young man."

The seriousness of the position, brought home to the American people by a succession of droughts and floods, has been realized, and there is now a Soil Conservation Service charged with the organization of remedial and preventive measures. How serious the situation is can be gathered from the estimate that only 30% of the land of the United States, and this includes much of the non-agricultural land, has been unaffected by harmful erosion, whilst over 40% has lost from one-quarter to three-quarters of its topsoil.

Much of the damage done is irreparable; but enough is known of the mechanism of soil destruction for preventive and, to some extent remedial, measures to be undertaken. The principal task is to prevent water from flowing across the face of the soil—in other words to reduce run-off (see p. 93) to a minimum. This can be done by such means as levelling gradients through terracing, by strip cropping, and by contour ploughing, but above all, by increasing the ability of the soil to absorb rainfall. The latter method implies the regeneration of soil structure and organic matter content. To me this appears the most desirable method, for it implies a return towards the stability of natural conditions.

Structure and water-holding capacity can be regenerated by reafforestation: the same object can also be attained by the establishment of grassland. If grassland could be established as easily in the United States as in Wales, the erosion problem would probably never have arisen and could easily be solved. It does appear, looking across the width of the Atlantic, that the possibilities of long grass leys, perhaps not so long as we have in Wales, should be actively explored. In the drier regions of the west, much of the land that has been under the plough must revert to range, and the evil of over-stocking must be abated in soils that have remained in range. The problem is being actively attacked by the Soil Conservation Service, and it may be hoped that the menace of soil destruction is in sight of being overcome.

One of the most instructive examples of soil conservation work is the work of the Tennessee Valley Authority, the so-called T.V.A. I need not remind you that the American Constitution sometimes opposes difficulties to public action, particularly when several states are involved. These difficulties were apparently circumvented in the Tennessee Valley, which includes portions of Tennessee, Georgia, Alabama, N. Carolina, and Virginia, by proposing the innocent object of improving the navigation of the Tennessee River. Now in order to obtain a minimum depth of water up to a certain point, it is necessary to equalize the flow by reducing the fluctuations

between flood and extreme low water. This implies the construction of dams and reservoirs. But reservoirs must be protected from silting up. And for this reason, and also to equalize the flow of rain-water into the river systems, it is necessary to minimize erosion. Here, then, is the opportunity for the land policy of the T.V.A.

I have not the space to follow all the activities of this remarkable organization. They include power distribution, industrial development, educational, social, and health services. Some of these activities may be criticized by those conversant with the local circumstances. You and I, however, may learn from the work of the T.V.A. how closely interrelated are the use of the soil and the life of the community, and how a desperate situation, for the case of the Tennessee Valley was desperate, may be retrieved by intelligent and co-ordinated effort.

I have devoted this letter mainly to American affairs. America is always interesting and dramatic, but from these happenings we may learn lessons for our own Empire. Indeed, in neighbouring Canada, similar events have occurred. We have seen the once prosperous prairies stricken by drought and wind erosion. But it is in the tropics above all that the menace of soil destruction by erosion is most serious. Although we have not seen the spectacle of the soil resources of a great country being squandered, the waste of soil by erosion has probably been equally great in the sum, and is still pro-

ceeding. Many warnings have been given by workers overseas, and it may be hoped that they will not pass unregarded.

The luxuriance of tropical vegetation can convey an entirely wrong idea of the agricultural potentialities of the soil on which it grows. It must be remembered that, under virgin conditions, plant nutrients form a kind of closed cycle, because practically all plant food taken from the soil is returned in the form of plant residues. Immediately this closed cycle is broken and crops are taken from the land, the need for replacement arises. Even more serious than the manurial position is the problem of loss of structure, erosion, and soil destruction. And, therefore, when tropical soils are brought into cultivation, soil conservation should always take precedence over soil exploitation.

Outside the British Empire, there are abundant examples of soil destruction through reckless exploitation. The derelict eroded foothills of western China have their reflection in the disastrous floods in the valleys of eastern China. In northern Africa, ruined cities in the desert mark the centres of once-prosperous agricultural regions.

We in Britain are more fortunate. Our grasslands are by their nature safe from erosion. The inclusion of grass leys in our arable rotations and the maintenance of organic matter status by the use of farmyard manure all contribute to maintain that structure which is so necessary for

stability. I will not say that I have not seen serious erosion in this country, but it is safe to say that the proportion of land thus damaged would be only a small fraction of one per cent. Normal erosion does occur, and we are accustomed to find shallow soils on hill tops, with deeper accumulations below. Severe erosion may have occurred in past generations in our uplands, consequent on deforestation, but the establishment of a grass cover now holds it in check.

If we, in Britain, do not suffer from destructive erosion, we are not free from other kinds of soil deterioration. We have one of the best climates in the world, with its abundant and well-distributed rainfall, and its general mildness, permitting growth practically throughout the year. Yet these favours of Nature do not exempt our farmers from the necessity for constant care. Our natural vegetation is heath, forest, and swamp, and these are waiting to repossess the land won from them. During the years of agricultural depression, we saw soils, improved in past generations by artificial drainage, reverting through neglect to their former wretchedness; we saw soils reverting to grass heath or heath, through neglect of liming; and we saw pastures invaded by useless bracken through bad management. One of the most heartening features of the war years has been the spectacle of so many of these derelict areas being brought to carry crops and grass.

You are greatly interested in the improvement

of our waste lands, and I agree that they offer possibilities for great increase in production. But what of the enormous possibilities still remaining in the reconditioning and improvement of our neglected farm lands? There is nothing more depressing than to see land that might be carrying fine grass, or growing bumper crops, abandoned to rushes or foggy pasture. The present campaign for improvement in grassland as part of the general raising of soil fertility offers the possibility, not simply of restoring our derelict lands to their former state, but of raising them to a still higher grade of productivity. Will our farmers respond to the challenge? The cynic may ask, will it pay them to respond?

Ever yours,

G. W. R.

Letter XVII

CONCLUDING REFLECTIONS*

My dear Stapledon,

I have tried to tell you about the soil as a material and the soil as an individual. I have tried to explain its relationship to the rocky crust that lies below it and to the plants that grow upon it. In this last letter, I want to recur to the contrast between soil in its virgin condition, a condition of stability and equilibrium, and the soil as exploited by man, losing, or in danger of losing, its natural structure, and yielding up its plant nutrient elements in the crops removed from it.

In primitive societies, with their sparse population, exploitation is inappreciable, for centres of cultivation are sporadic and shifting, so that, even

*In this concluding letter, which is rather more personal than those which have preceded it, I have ventured to intrude personal opinions and prejudices that may appear somewhat reactionary. Knowing how difficult it is to discover truth, and remembering how many learned authorities may be found on opposite sides of most questions, I would not assign to some of the ideas here put forward any greater weight than that belonging to most personal opinions. The general reader may either omit the perusal of this letter, without losing the essential argument of the book, or he may read it as a diversion from the more serious matter that has preceded it.

if small areas are worked out, they are abandoned to the natural forces of recuperation. With progress in civilization, stable agriculture evolves, made possible by conservative methods involving the return through feeding animals of plant nutrients taken from the soil in crops. Such was the agriculture, depicted after it had passed away, of Virgil's Georgics: such was the agriculture of our own country at the close of the eighteenth century. The self-supporting agriculture of Rome broke down with increase in population and the influx of supplies of corn from overseas. Our own self-sufficiency broke down under similar circumstances. The growth of urban industrial populations demanded production at a more rapid rate than was possible under conservative systems of agriculture and led to the mining of soil fertility by the exhaustive cropping of virgin lands overseas. How disastrous that exploitation has been I have already attempted to show.

The tragic consequences of plundering the reserves of fertility in virgin soils have already been realized in the United States, and it is unlikely that spoliation will proceed further. It is as inevitable as it is imperative that similar exploitation should eventually cease in other parts of the world. It was an unforeseen but apparently necessary evil; if the development of new lands had proceeded along conservative instead of exhaustive lines, the rate of colonization would have been slower and production would scarcely have kept pace with the growth of population conse-

quent on industrial development. Had industrial development been less precipitate, it might have been possible to avoid the destruction which has occurred.

The exhaustive exploitation of the accumulated fertility of virgin lands is not the only expedient by which growing demands for production can be met. Modern knowledge of the principles of plant nutrition and the skill of the plant breeder have in some measure exempted us from the former limitations of conservative utilization of the soil. By the use of artificial fertilizers, it is now possible, not only to maintain the plant nutrient status of soils, but to obtain yields far above those obtained under the older systems. Much of the agricultural research of the past century has had for its aim the increase of production by the use of artificial fertilizers. Hence the multiplicity of manurial experiments and the refined technique of modern statistical methods.

If the possibilities of meeting the demand for food by exploiting virgin lands are curtailed in the future, either by plan or of necessity, can we look forward to production based on the more intensive use of artificial fertilizers? If we knew enough about plant nutrition, it might appear possible to meet future demands in this way. The soil might become a mere vehicle for plant food supplied in fertilizers and an anchorage for roots. Indeed, we might even go a stage further and dispense with the soil altogether, for Professor Gericke, of California, has shown how the "dirt may be

taken out of farming" by growing enormous crops in artificially heated water cultures. It is not difficult to imagine possibilities in the growth of crops on coastal sands with controlled ground-water conditions, adding all the necessary plant food in compound fertilizers.

Up to the beginning of the nineteenth century, progress in science had comparatively little effect on practice in the arts, and, one might almost say, no effect on the oldest of the arts, agriculture. Since then, the impact of science on life has steadily increased, until there is now scarcely a department that is not affected by the relentless growth of knowledge. But, although agriculture has drawn increasingly on the results of science, it is by no means so closely controlled as are the other branches of human activity. This state of affairs is almost inherent in the nature of agriculture, which does not lend itself to large-scale organization and rationalization, but is largely in the hands of small operators. And, whilst some may deplore the slowness of farmers to use the results of science, here, if anywhere, conservatism may plead some justification, for not only have advances in knowledge been slower and less certain, but the consequences of too hasty innovation might be disastrous alike to soil and farmer.

The optimist may look forward to a time when our knowledge of the soil and of plant nutrition will be so increased that all the food we need can be either synthesized or else grown by the methods of scientific industry, a time when

"... *omnis feret omnia tellus.*"

A less sanguine philosopher may feel some doubts as to the desirability of such a revolution in methods of food production. He may shrink from the consequences of Man obtaining complete control over the forces of Nature as exhibited in the growth of plants. Having in mind the dire examples of the abuse of the power over Nature given by Science, he may remember with approval good old Doctor Opimian's words* :—" *Science is one thing, and wisdom is another. Science is an edged tool, with which men play like children and cut their own fingers. If you look at the evils which science has brought in its train, you will find them to consist almost wholly in the elements of mischief. . . . The day would fail if I should attempt to enumerate the evils which science has inflicted on mankind. I almost think it is the ultimate destiny of science to exterminate the human race.*"

We in 1946 may agree that the last sentence is not so fanciful as it seemed in the middle of the nineteenth century. Even if we cannot concur entirely in Dr. Opimian's melancholy estimate of the value of science, we may entertain misgivings as to the probable value for humanity of being able to exploit, not the limited resources of the soil, but the almost limitless stores of solar energy to supply sustenance. It is not my task, even if I were able, to indicate the possible perils involved in a complete mastery of the mechanism of plant growth. Ask yourself, my dear Stapledon, if

* In " Gryll Grange," by Thomas Love Peacock.

Man has used wisely the enormous power which he has already acquired over Nature. Is there any evidence that further power will be used more wisely?

Guglielmo Ferrero,* the historian of Rome, contrasts the modern ideal of power with the older ideal of perfection, identified by him with Greco-Latin culture. The ideal of perfection is a legacy of the past; it includes the Greco-Latin literary and artistic tradition; it includes Christian morality, and imposes on us beauty, truth, justice, and moral perfection as the aims of life. Contrasted with this is the ideal of human power over Nature; the ideal of material welfare as the highest good; the ideal, influenced by crude ideas of evolution, that lures on mankind with the belief in the inevitability of progress. The ideal of perfection implies the recognition of appointed limits to all human activity. The ideal of power knows no such limits but drives man relentlessly along a path no longer of his own choosing.

The day may seem far distant when the progress of Science will enable the last shackles of Virgilian husbandry to be shaken off. Yet half a century ago it would have appeared as fanciful to speculate on the probable consequences of the conquest of the air, an achievement that has now proved almost an unmixed evil to humanity. Bearing in mind the tragic consequences that have followed the pursuit and attainment of the ideal of power, it is permissible to hope that this

*In "Le Génie Latin," Grasset, Paris, 1917.

ideal may not govern the future of our agriculture. Yet there must be development; perhaps there should be a plan; but in order to make a plan we must know the future for which it is intended. To-day's plan may be shattered by the conditions of a decade hence.

If it is not possible to have a plan, we may at least have principles; and the first and greatest that my studies have taught me is that we should not allow our agricultural soils to depart too far from virgin conditions. This does not mean return to forest but rather that renewal which the soil undergoes in grass. In an earlier letter,* I spoke of the great fertility of newly-broken prairie soils. The soil of a well managed pasture is essentially a prairie soil. I would wish, therefore, for a system under which all our agricultural soils could periodically renew themselves under grass. To be more explicit, I am pleading that our arable soils should be under rotations, including three or more, and preferably more, years of grass ley. You have arrived at similar conclusions, and I would join with you also in urging that our permanent grasslands, with few exceptions, should be ploughed up, and, after a decent interval under arable, laid down again as temporary leys. If these aspirations were realized, the distinction between arable and grassland would largely disappear, except for certain areas, such as the grazing grounds of Leicestershire and Romney Marsh, where nature and skill have combined to maintain grassland permanently in the highest productivity.

*See page 76.

As to our waste and hill lands, I would like to see a much larger area than you would willingly surrender, including some of the agrostis-fescue pastures, afforested, though not exclusively with conifers. This might mean some reorganization of the sheep industry, but the loss of grazing in the "ffridd" lands might be more than made good by improvement of the lands under cultivation.

The utilization of our soil on these principles would be essentially conservative of our soil resources. It would provide a safe alternative to industrialization of agriculture. "Praise a large, but till a small demesne," said old Virgil, and I believe that the happiest future for our soil is neither in the ranch nor in the great mechanized farm. The greater the proportion of our people living on and interested in the soil, the greater will be our stability. And I would rather see production increased by levelling up the fertility of our neglected soils by means of long ley husbandry than by exacting the last bushel from our best soils with intensive manuring.

I am distrustful of Science in the service of the "ideal of power." May it never thus govern the use of our soil. But in the development of a conservative agriculture such as I have suggested, there are many tasks for Science to perform. The most important feature of such an agriculture would be grassland, and this should be the central object of agricultural research. I will not presume to outline the part which you as agrostologists (or

grass experts, if you will) have to play.* We as soil scientists must learn to know our soils better and to discover how they can be made to maintain your pasture plants in splendid condition. We must understand their moisture relationships, their lime status, and we may have to study those inconvenient "trace" elements that sometimes cause baffling deficiency diseases in stock. And perhaps, in years to come, we may have to learn economy in the use of external fertilizers, so that the object of our experiments may be, not how many tons or bushels per acre we can obtain, but how fertility can be most economically maintained.

The present improved state of our agriculture should not lead us to complacency. There is still not enough interest in the actual use of the soil. I suspect that under this indifference is an ingrained belief in the continued supply of cheap food from overseas. But these cheap and abundant supplies have depended largely on the ruthless exploitation of the natural resources of other lands, and cannot continue indefinitely. The countries on which we have depended must eventually develop stable systems of agriculture for themselves. And, with the increasing demands of their own populations, the day must come when exportable surpluses will shrink. Thus the old Malthusian bogey rises up again.

Viewing the future of the soils of the world and realizing that their resources for food production

*You have some stiff problems in finding out how to lav light soils in dry climates down to grass.

are more limited than was formerly supposed, I cannot avoid the conclusion that our own soil must bear a larger share in the provision of our food. The present campaign for raising the level of fertility of our soil has originated under the threat of war. It is no less necessary if we remain at peace. I believe that the solution of the problem will be found, not in the adoption of revolutionary and artificial methods, but in the enlightened yet conservative use of our natural resources of soil and climate, with Science always the servant but never the master.

Ever yours,

G. W. R.